NUMERICAL MODELING TECHNIQUES AND APPLICATIONS

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Tsunamis and Tsunami Warning Systems: Talk Structure

-Tsunamis:

- -Generation
- -Physical characteristics

-Tsunami Detection:

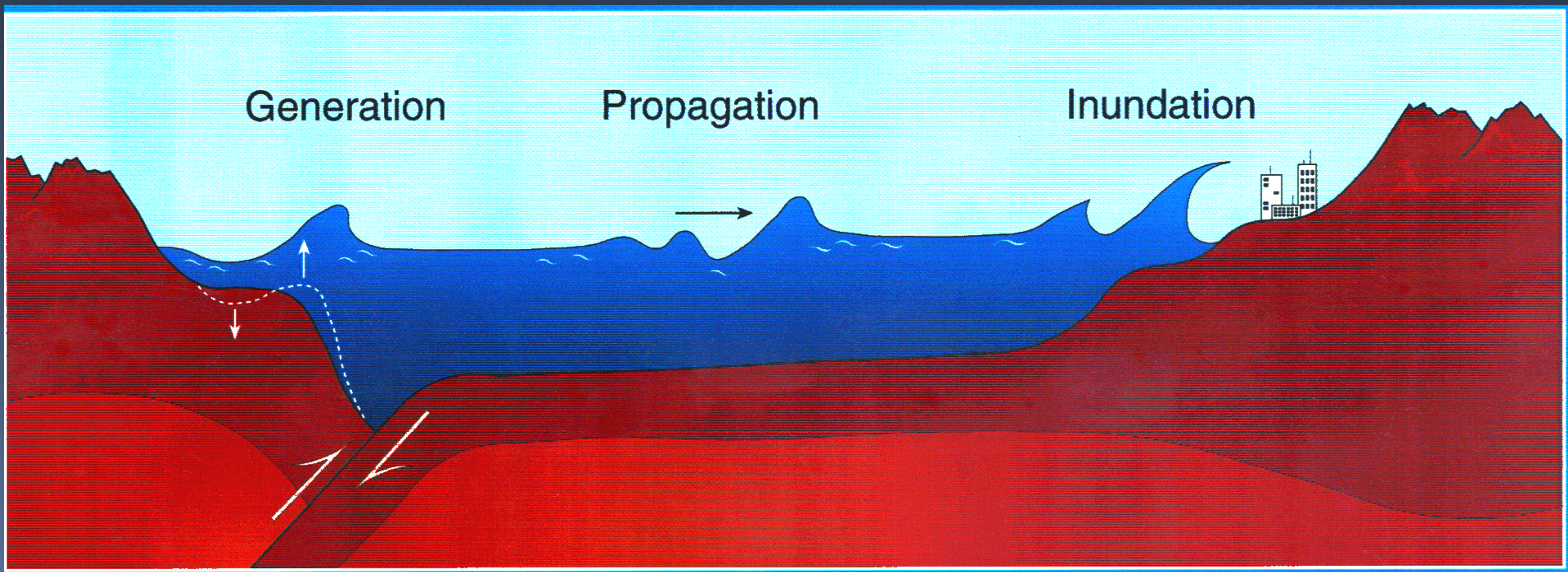
- -Earthquake Based
- -Tsunami Based

-Tsunami Forecasting:

- -Linearity in deep water.
- -Inversion of DART data.
- -Forecast Model Development.
- -Early events.
- -Chile, February 2010.

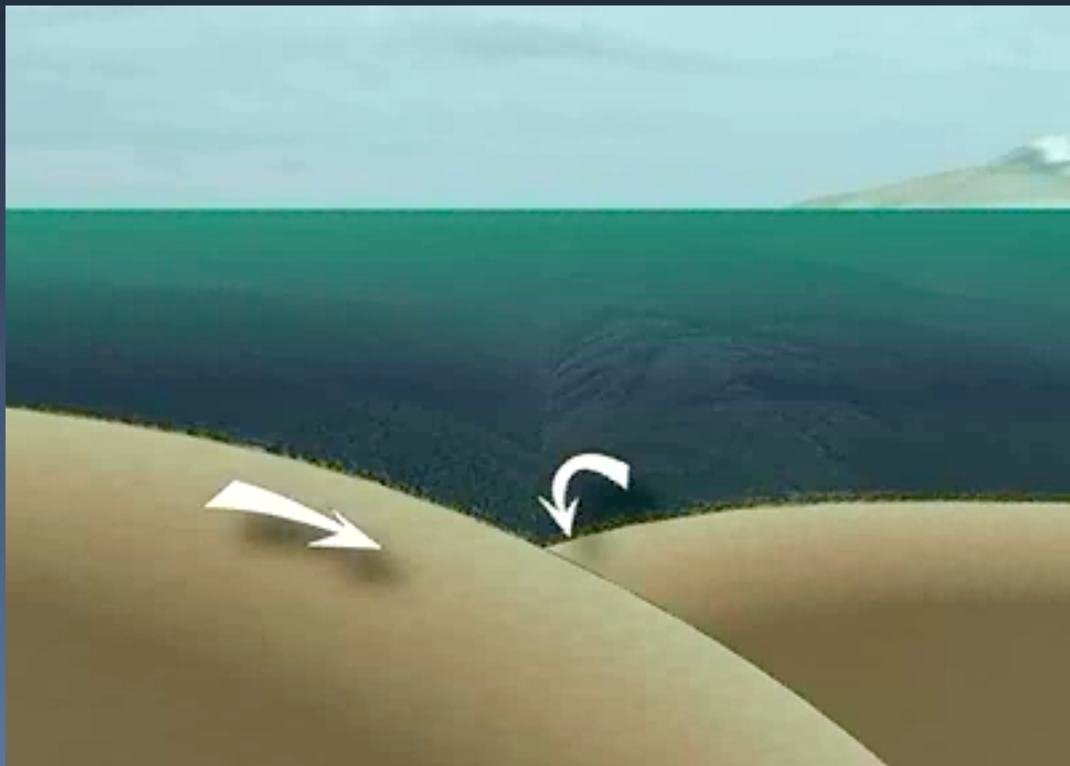
Three phases of tsunamis:

- Generation
- Propagation
- Inundation



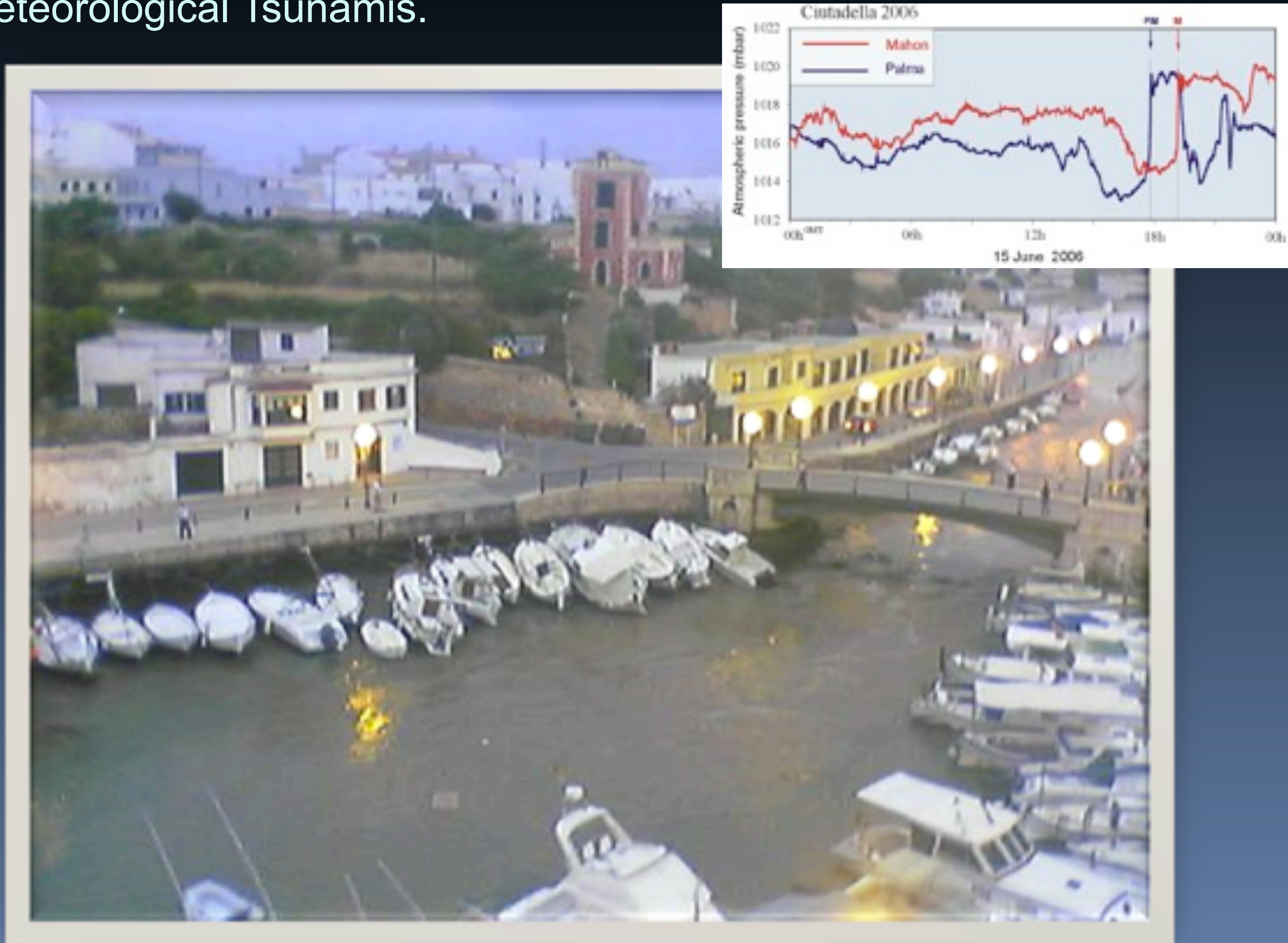
Tsunami Generation

Typical method: earthquake at plate boundary



Tsunamigenic Phenomena

- Meteorological Tsunamis.



Ciudadella, Spain, Tsunami June 15, 2006: Slide1

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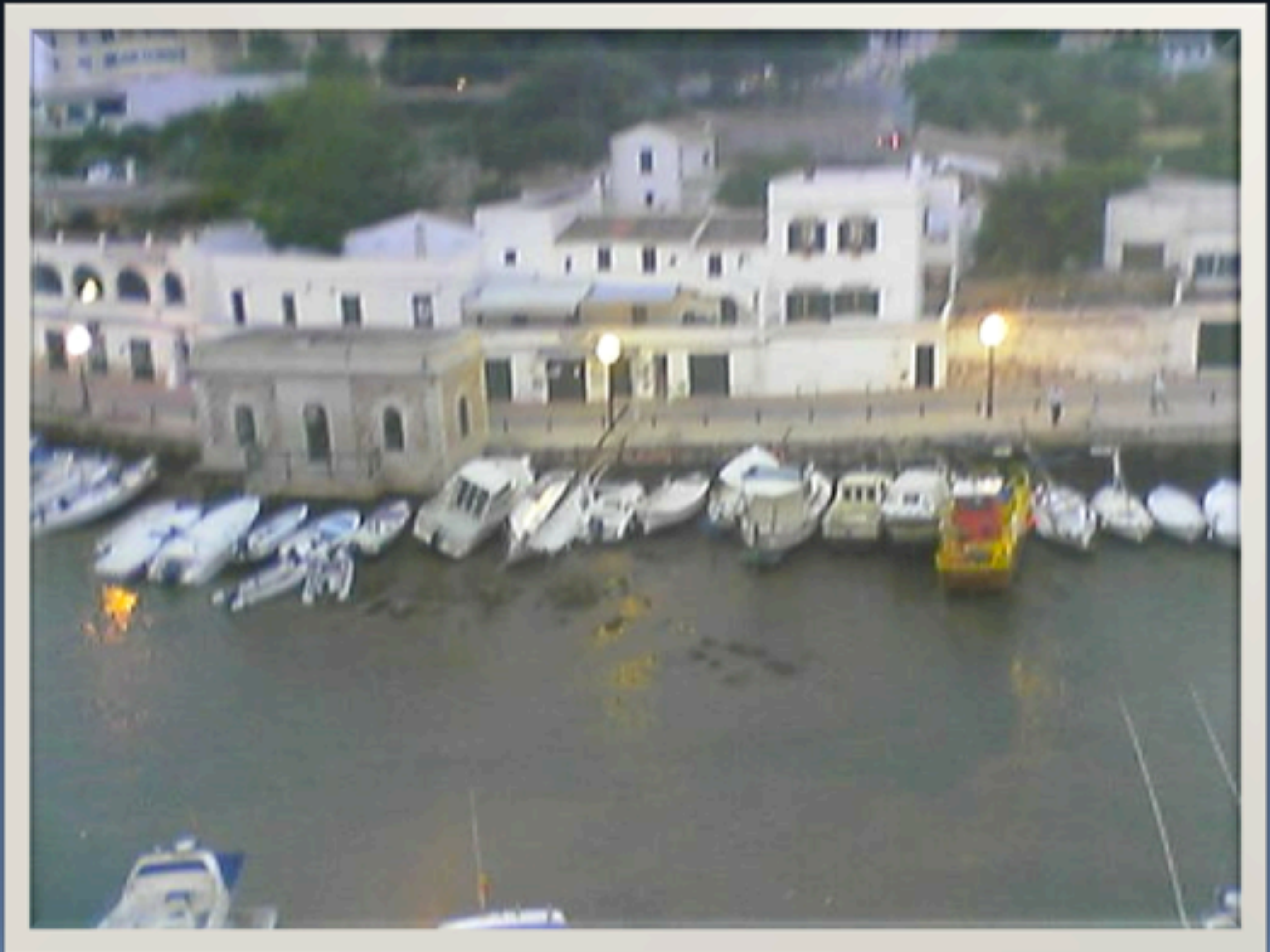

Ciudadella, Spain, Tsunami June 15, 2006 : Slide 2

Tsunamigenic Phenomena

- Meteorological Tsunamis.

Ciudadella, Spain, Tsunami June 15, 2006 : Slide 3

Tsunamigenic Phenomena

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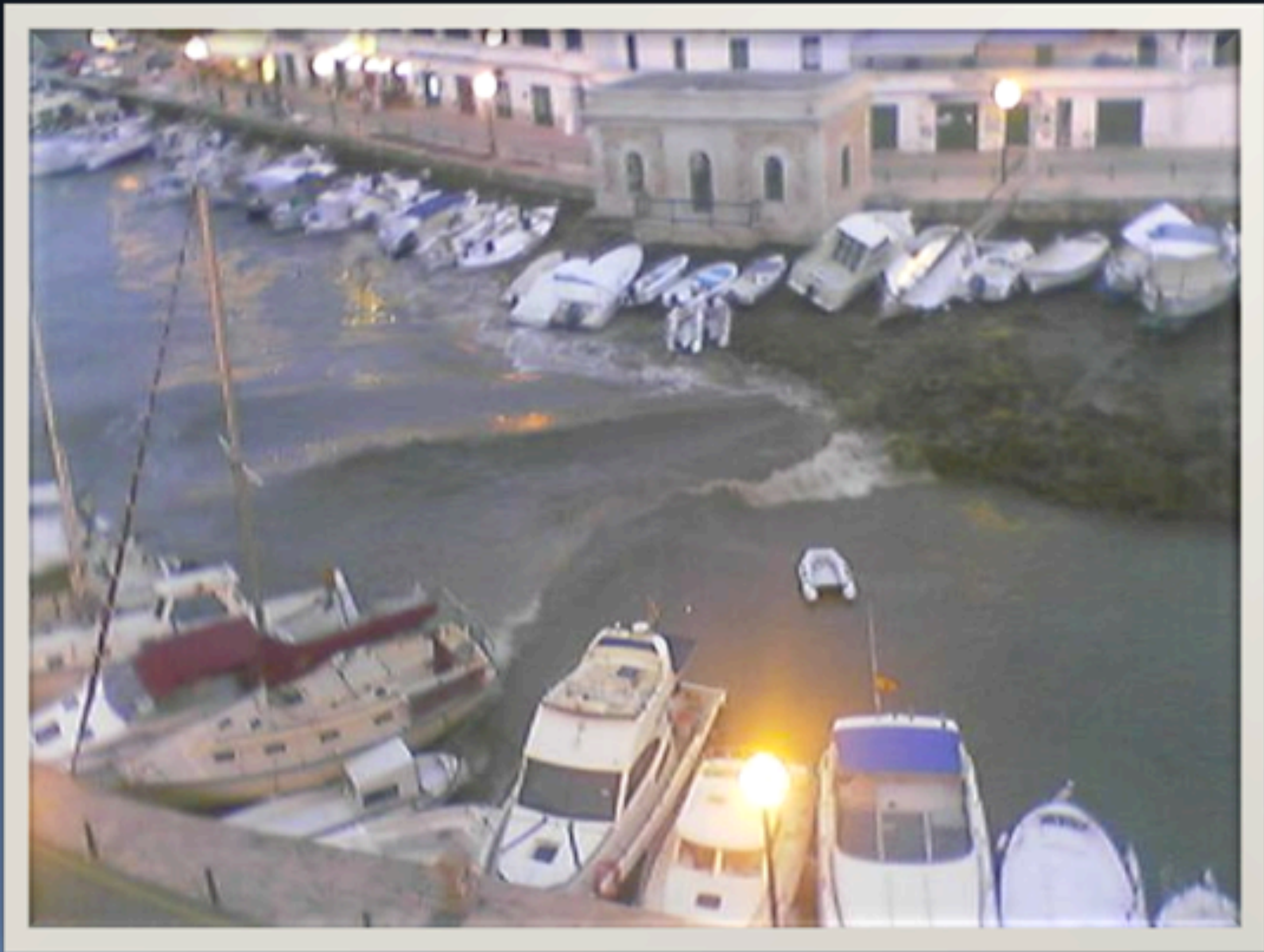
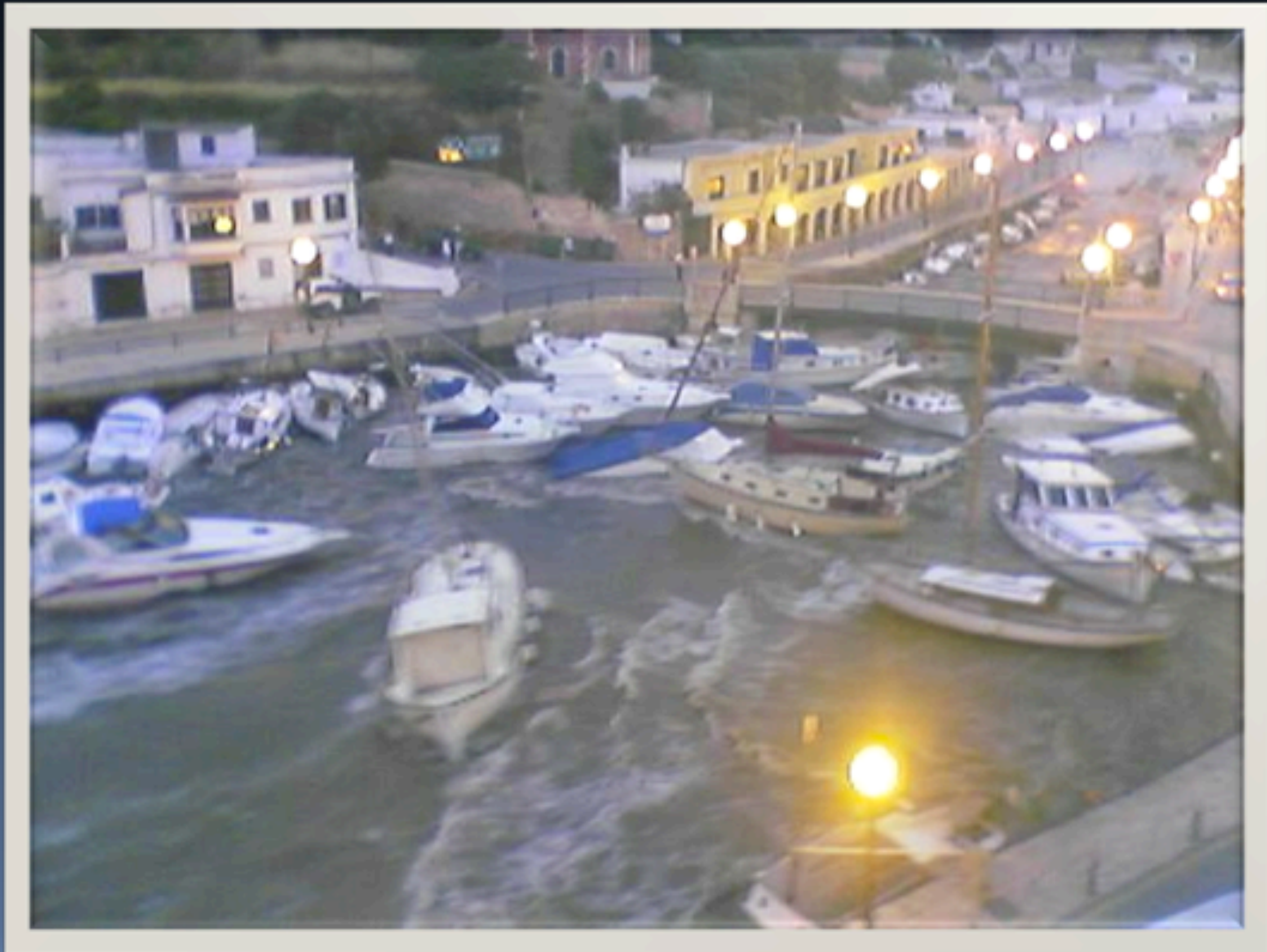


Ciudadella, Spain, Tsunami June 15, 2006 : Slide 4

Tsunamigenic Phenomena

•Meteorological Tsunamis.



Ciudadella, Spain, Tsunami June 15, 2006 : Slide 5

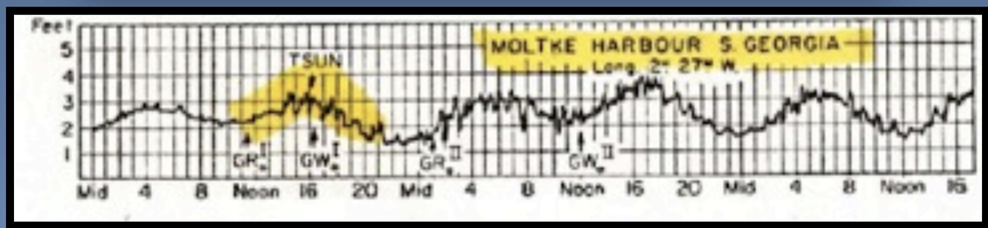
Tsunamigenic Phenomena

- Meteorological Tsunamis.

Ciudadella, Spain, Tsunami June 15, 2006 : Slide 6

Tsunamigenic Phenomena

- Tsunamis generated by volcanic explosions: Krakatoa, 1883
- They have the potential to generate a meteorological tsunami.



Tsunamigenic Phenomena

- Tsunamis generated by underwater land-slides: Lituya Bay, AK

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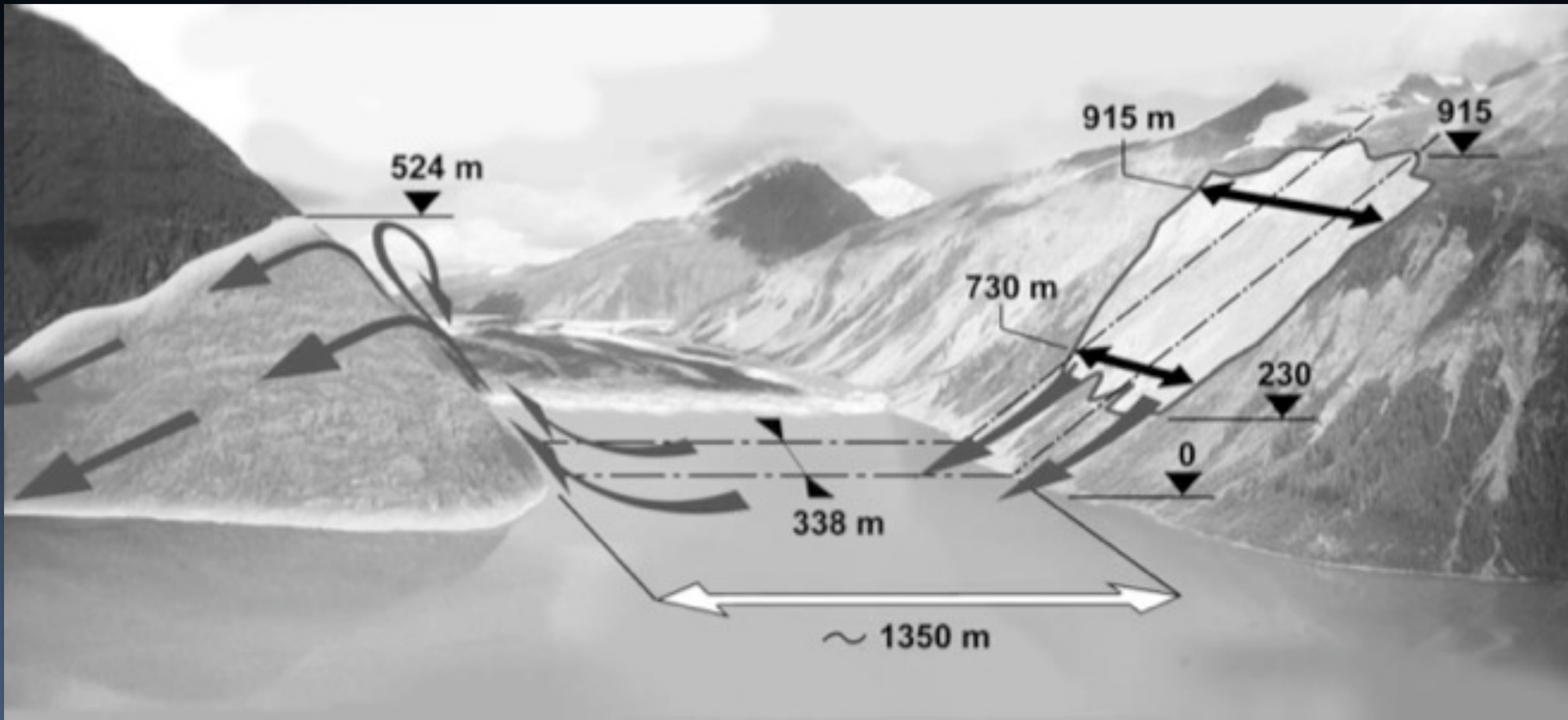
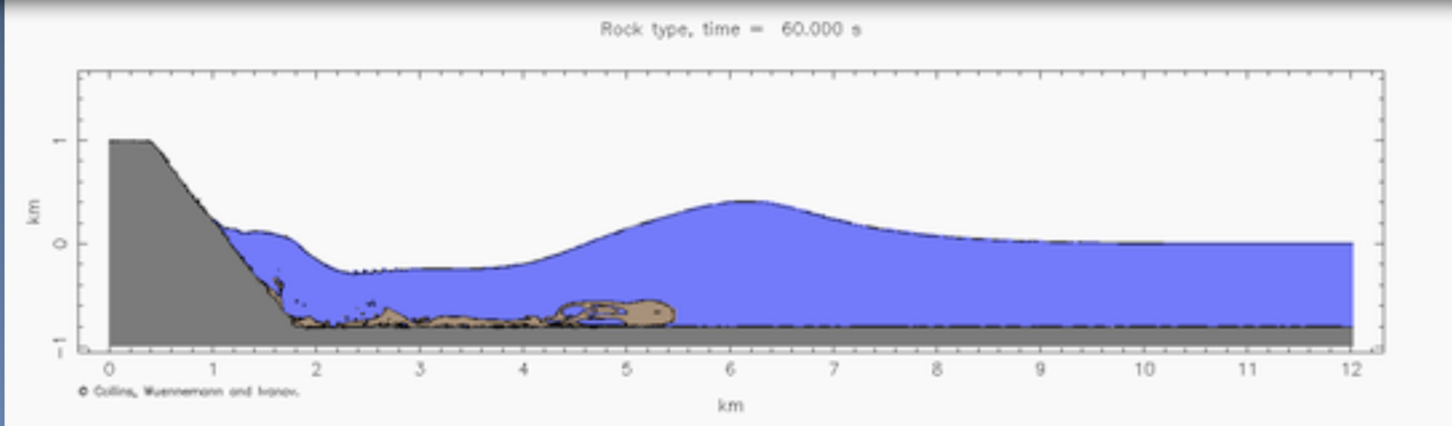
Tsunamigenic Phenomena





Tsunamigenic Phenomena

- Tsunamis generated by underwater land-slides: Aisén, Chile.
- Slope failure.

Tsunamigenic Phenomena

- Tsunamis generated by underwater land-slides: Aisén, Chile.

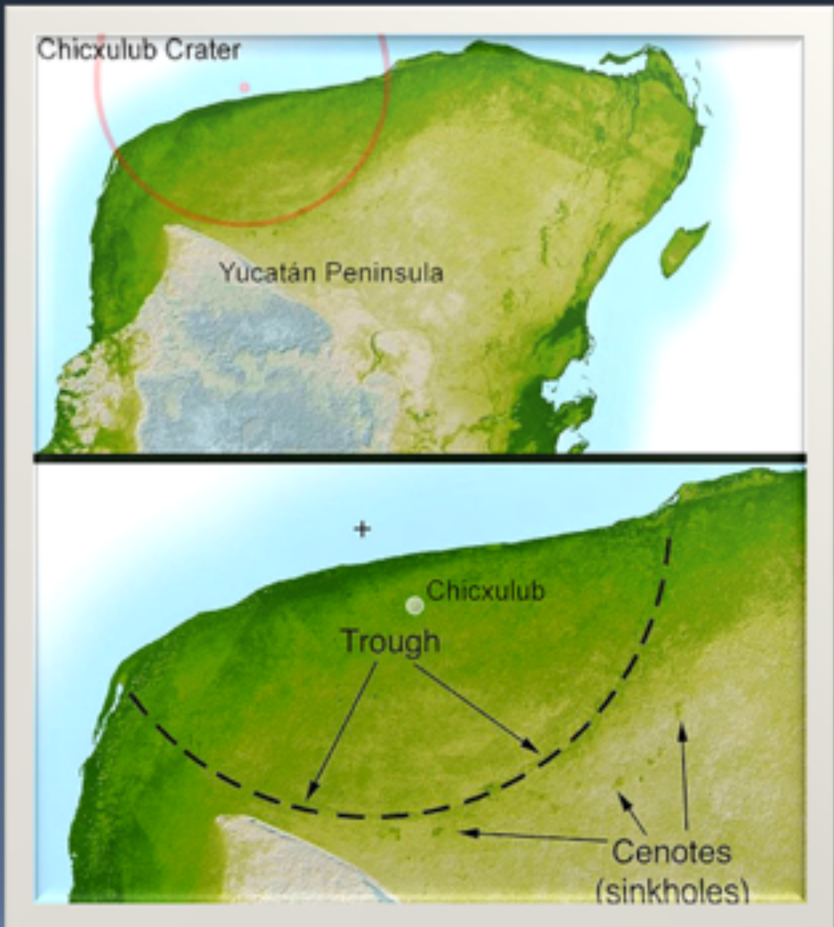
- Visible scars.

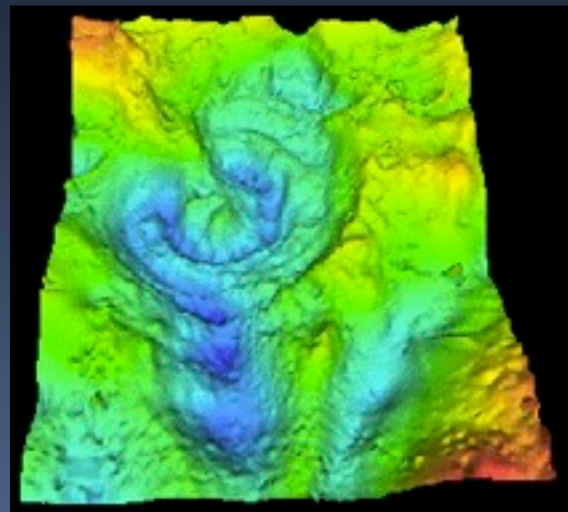
Tsunamigenic Phenomena

- Tsunamis generated by underwater land-slides: Aisén, Chile.
- Inundation.

Tsunamigenic Phenomena

- Tsunamis meteorite impacts.





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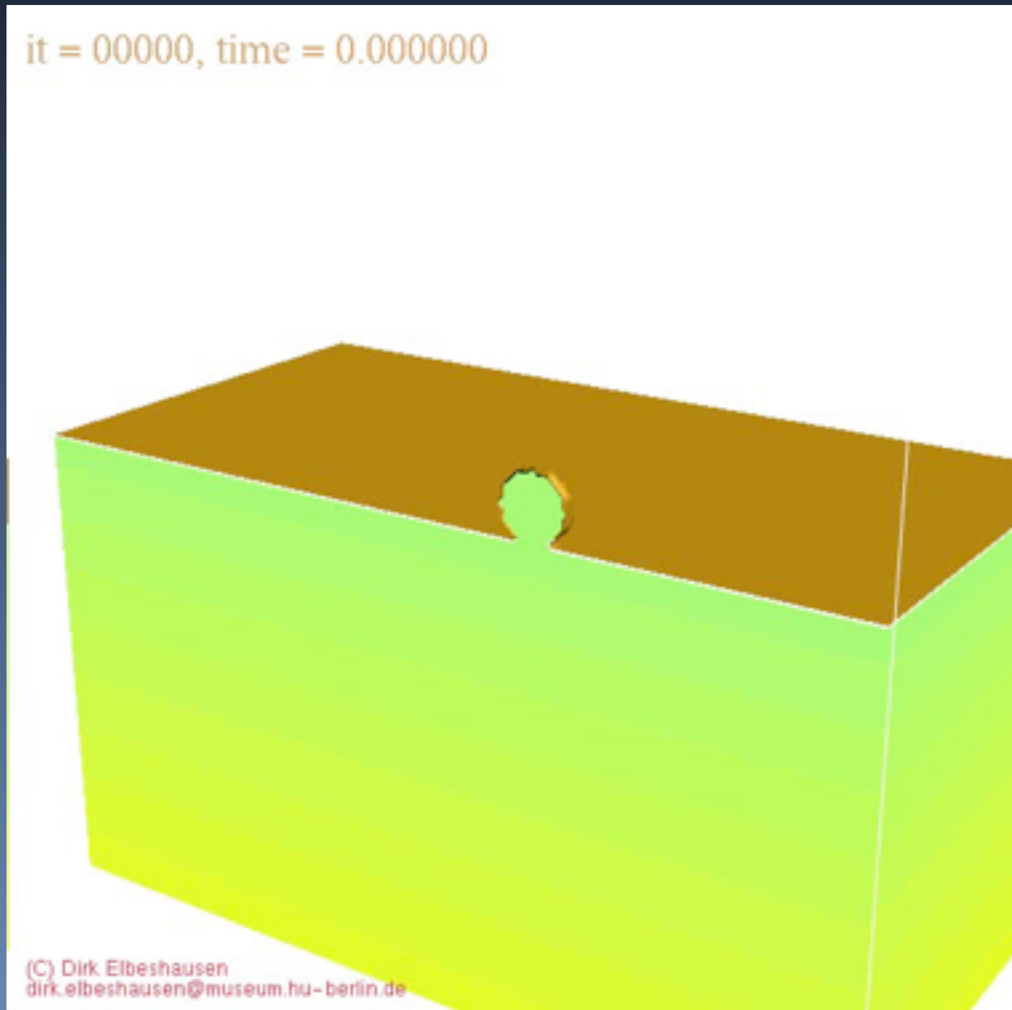
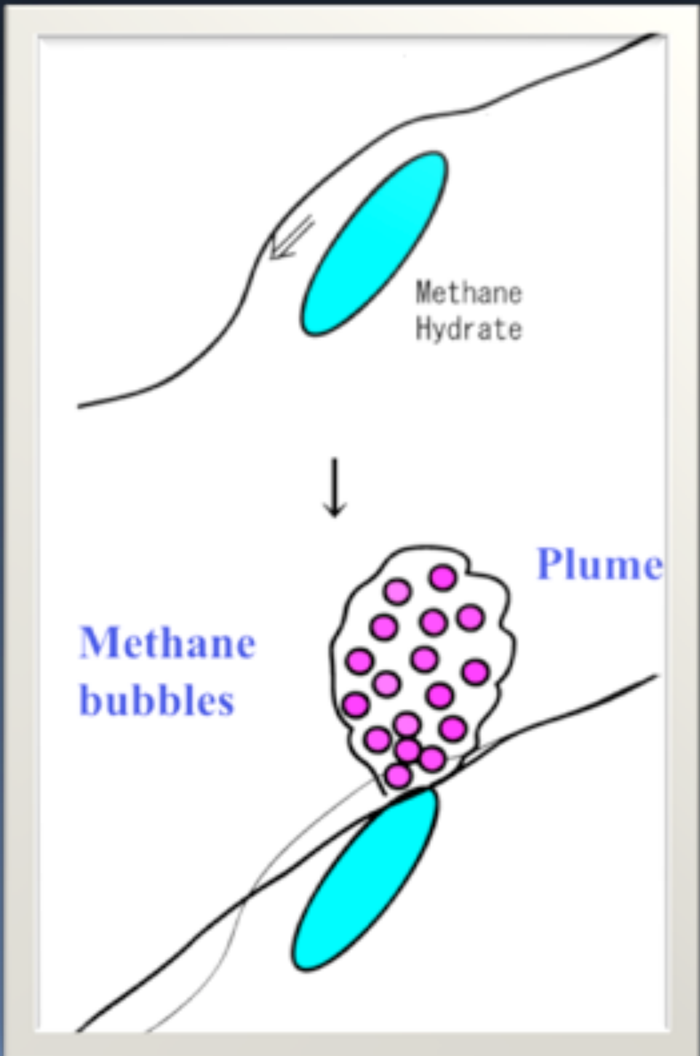
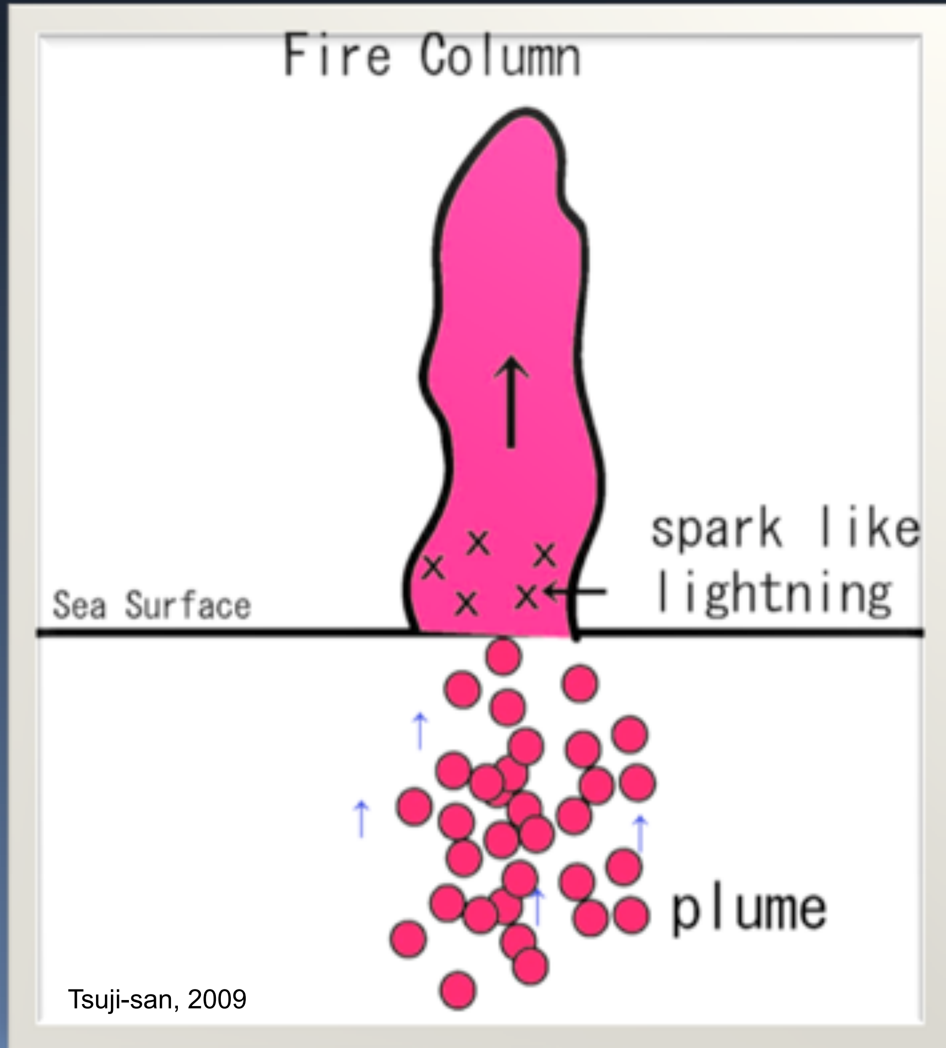


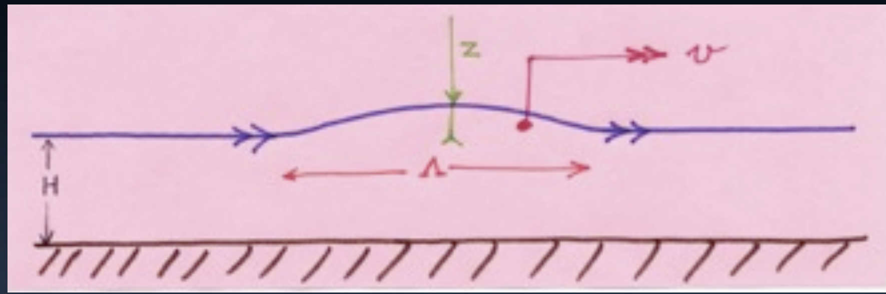
Tsunamigenic Phenomena

• Tsunamis generated by explosion of underwater methane deposits: Deep Water Horizon?





Physical Characteristics of a Tsunami in Deep Water



- Propagation Speed: Speed depends on ocean depth, H. $v = \sqrt{gH}$

  In practice: H=5 Km, v=220 m/s (~=800 Km/h)
  (approximate cruise velocity of a commercial airliner)

- Maximum Amplitude, z: from a few centimeters to a half meter.

- Typical Wavelength: Λ = 300 km (period ~ 600 s-3000s)

- A tsunami is always composed of several waves.

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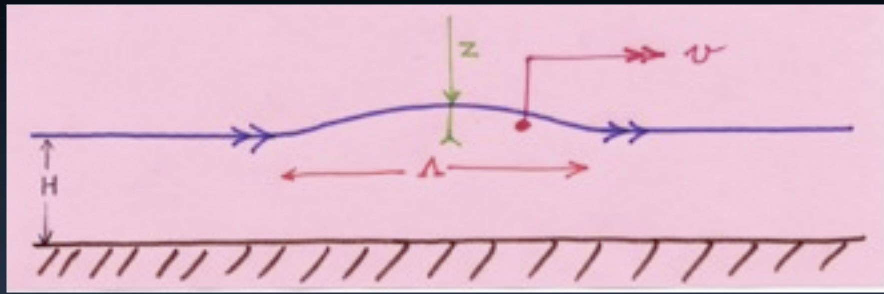

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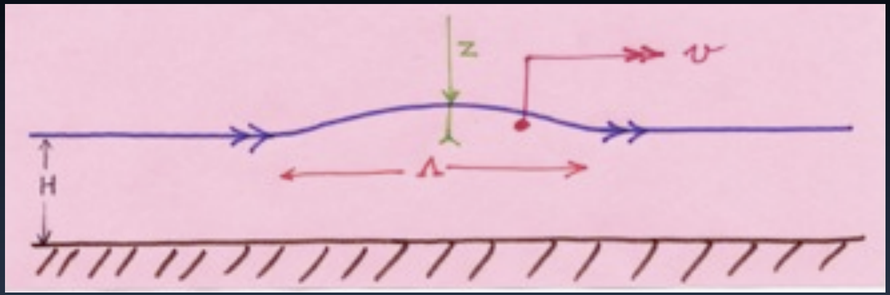

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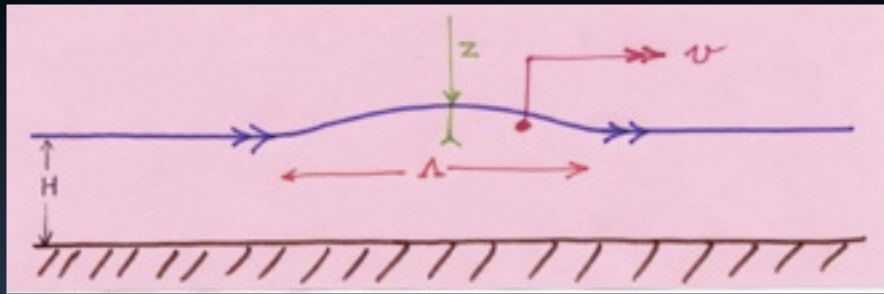

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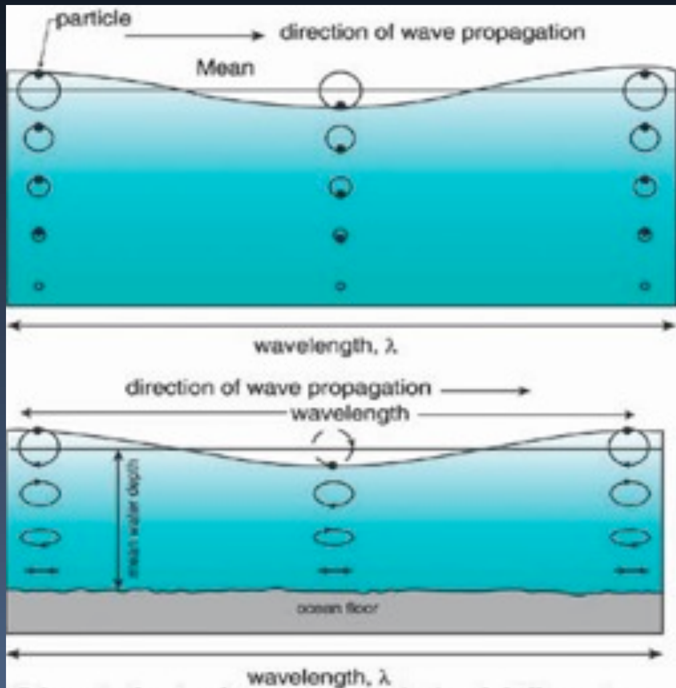
Physical Characteristics of a Tsunami in Deep Water

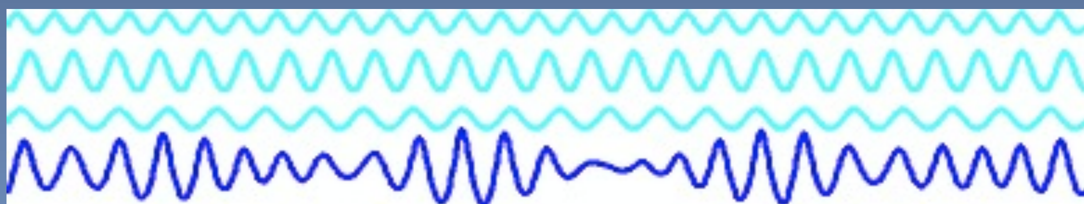
- A tsunami is always a long wave (alt. A wave in shallow water).



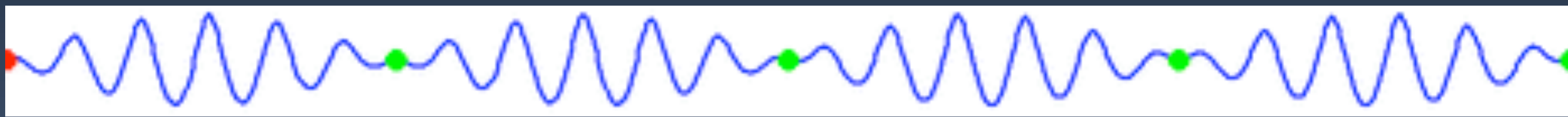
- A tsunami is a non-dispersive wave.

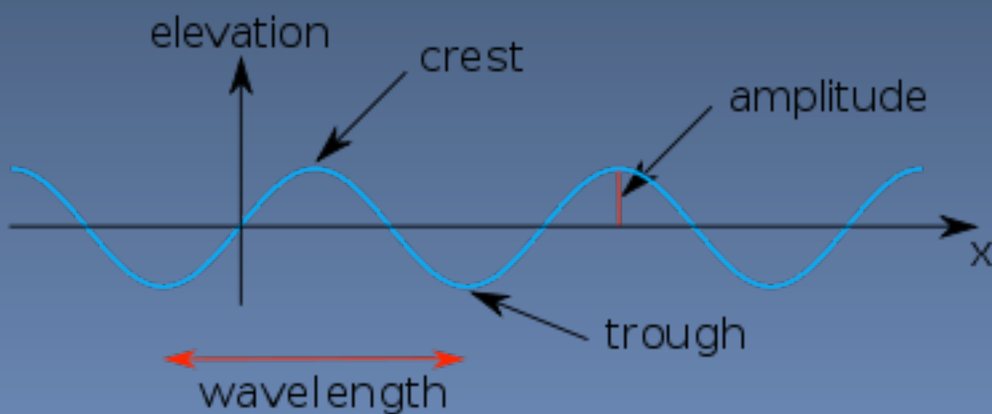
$$c = \frac{\omega}{k} = \sqrt{\frac{g \times Tanh(kH)}{k}}$$

Example of dispersive wave behavior

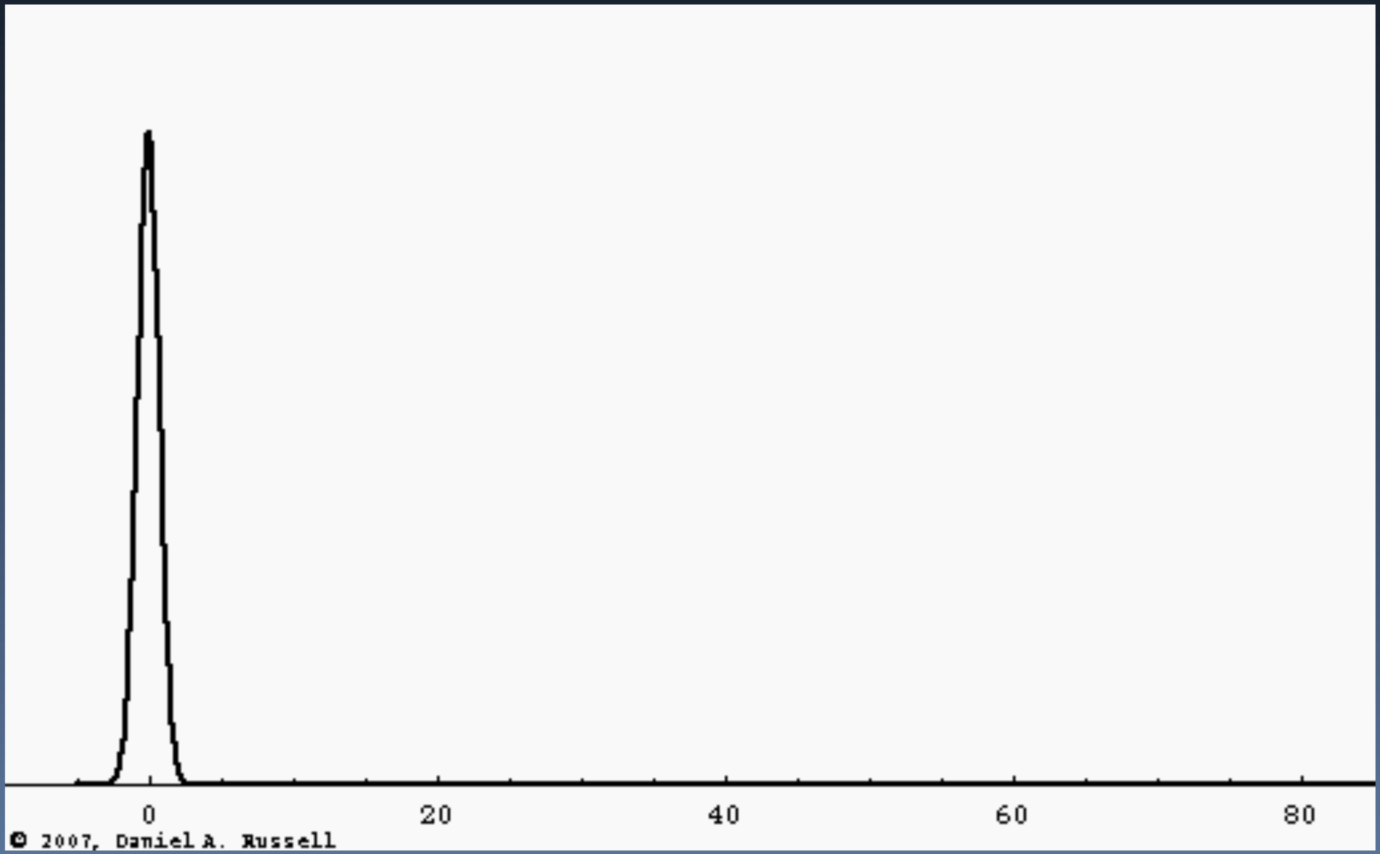


Wave Dispersion, cont'd

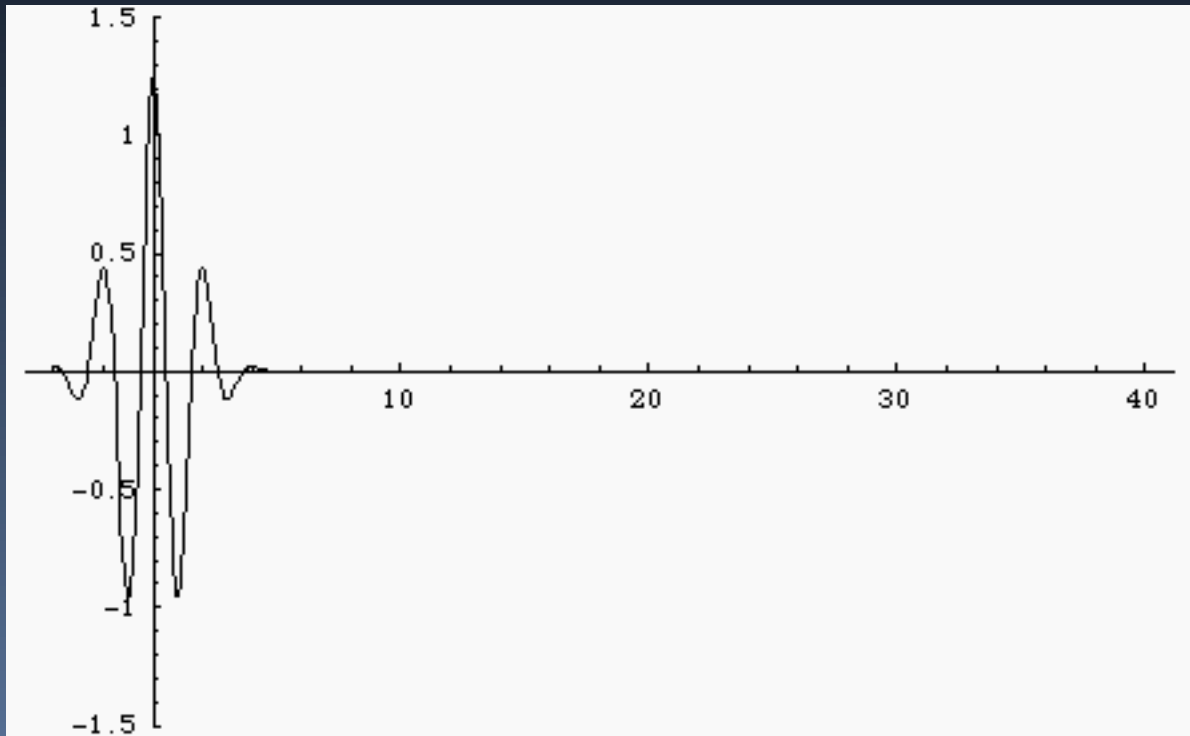




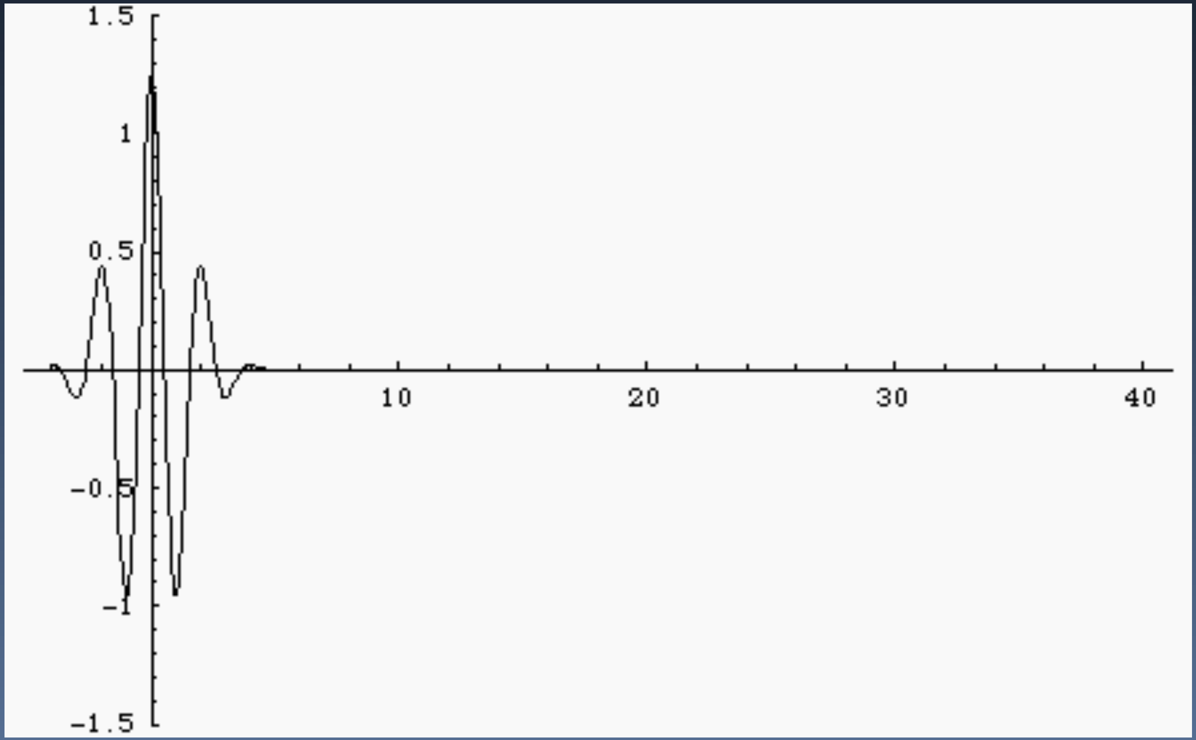
Wave Dispersion, cont'd



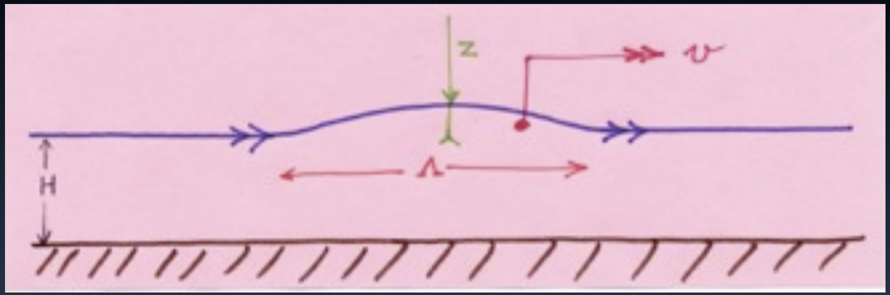
Wave Dispersion, cont’d



Wave Dispersion, cont'd

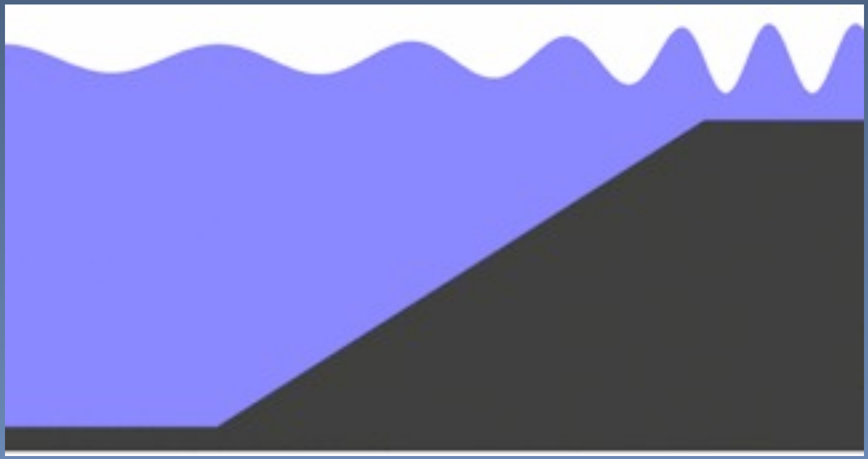


Physical Characteristics of a Tsunami in Shallow Water

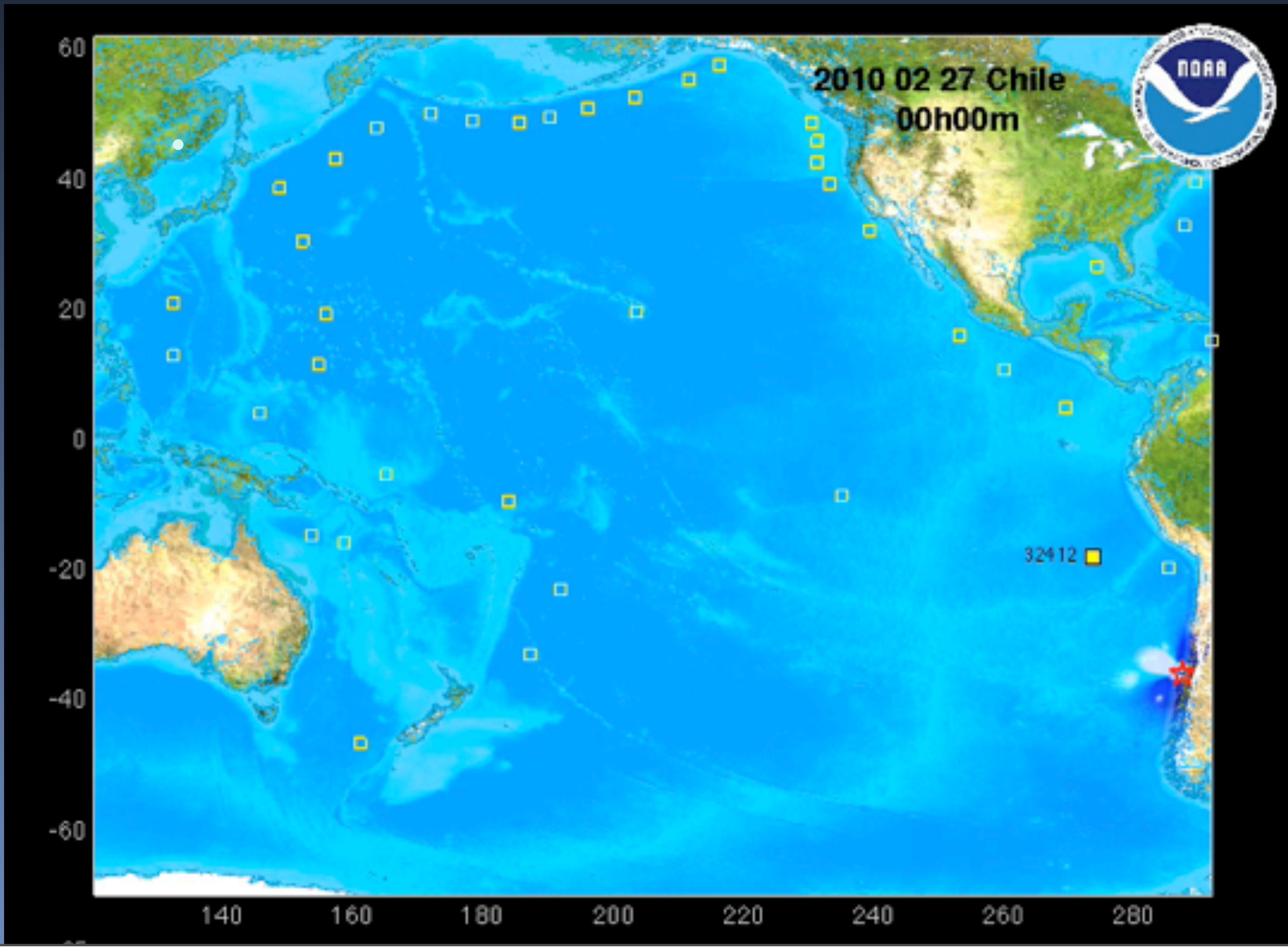


- Propagation Speed: Speed depends on ocean depth, H. $v = \sqrt{gH}$

- The leading part of the wave slows down as it enters shallow waters, the trailing part of the wave is still in deep water and moving faster than the leading part. This causes the wave height to increase and the wavelength to shorten.

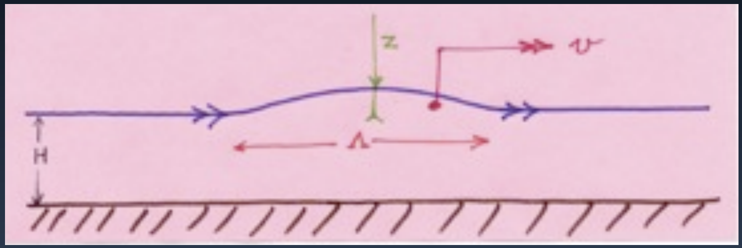


Refraction: waves bend when they go through a slower medium



$$v = \sqrt{gH}$$

Physical Characteristics of a Tsunami in Shallow Water.

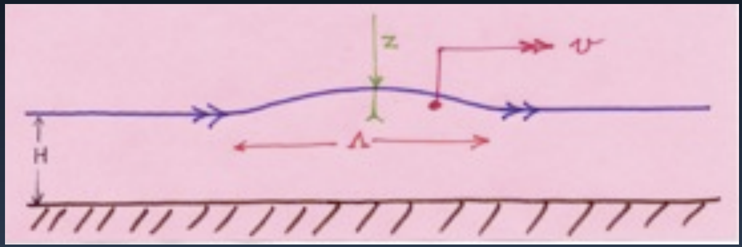


• Tsunami wave heights in shallow water can reach tens of meters.

• Typical wavelengths will range between 10-20 Km.

• The size of the tsunami wavelength makes it much more destructive than storm waves.

Physical Characteristics of a Tsunami in Shallow Water.



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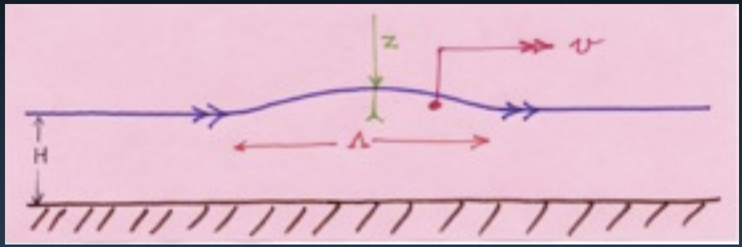

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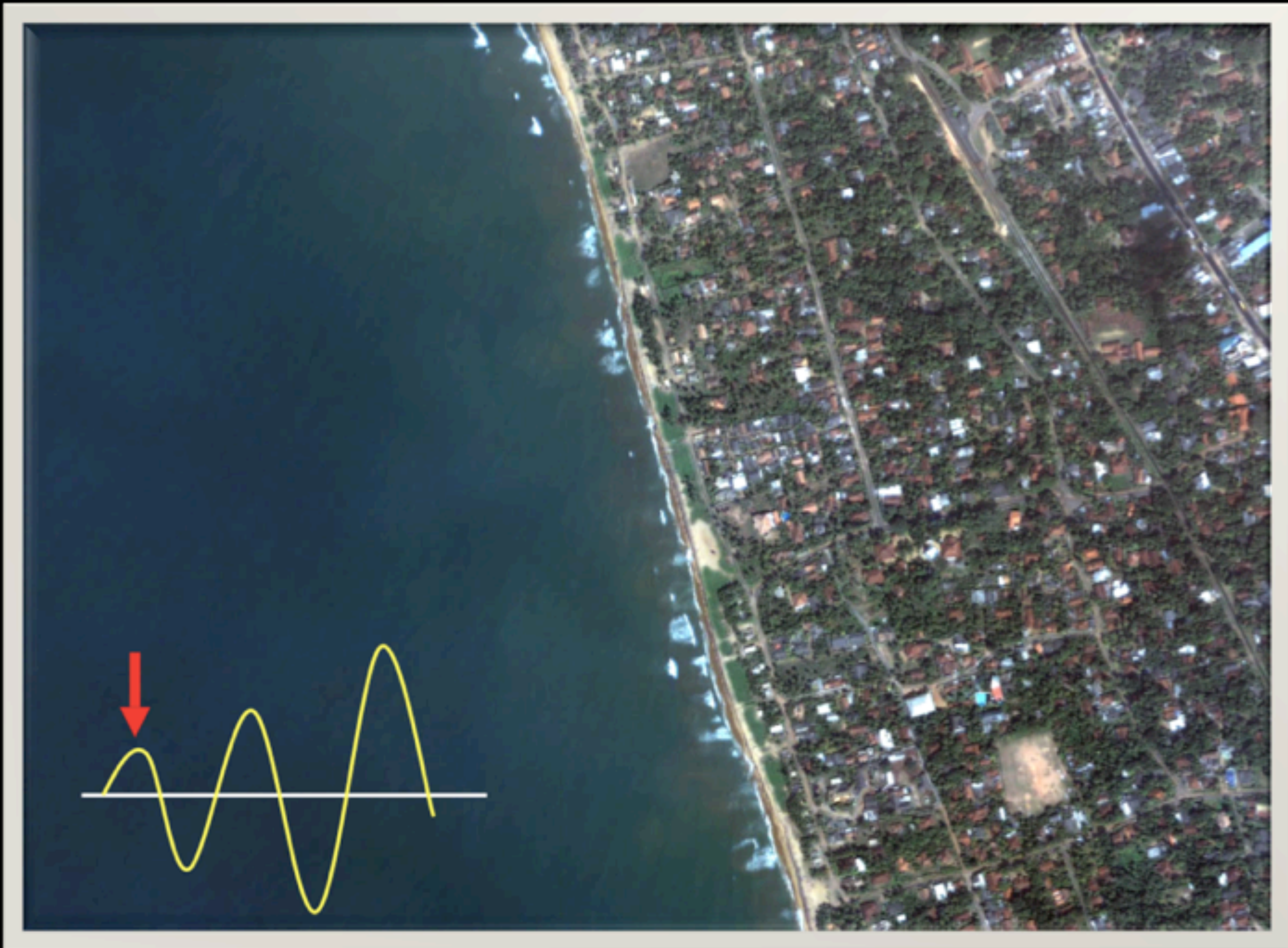
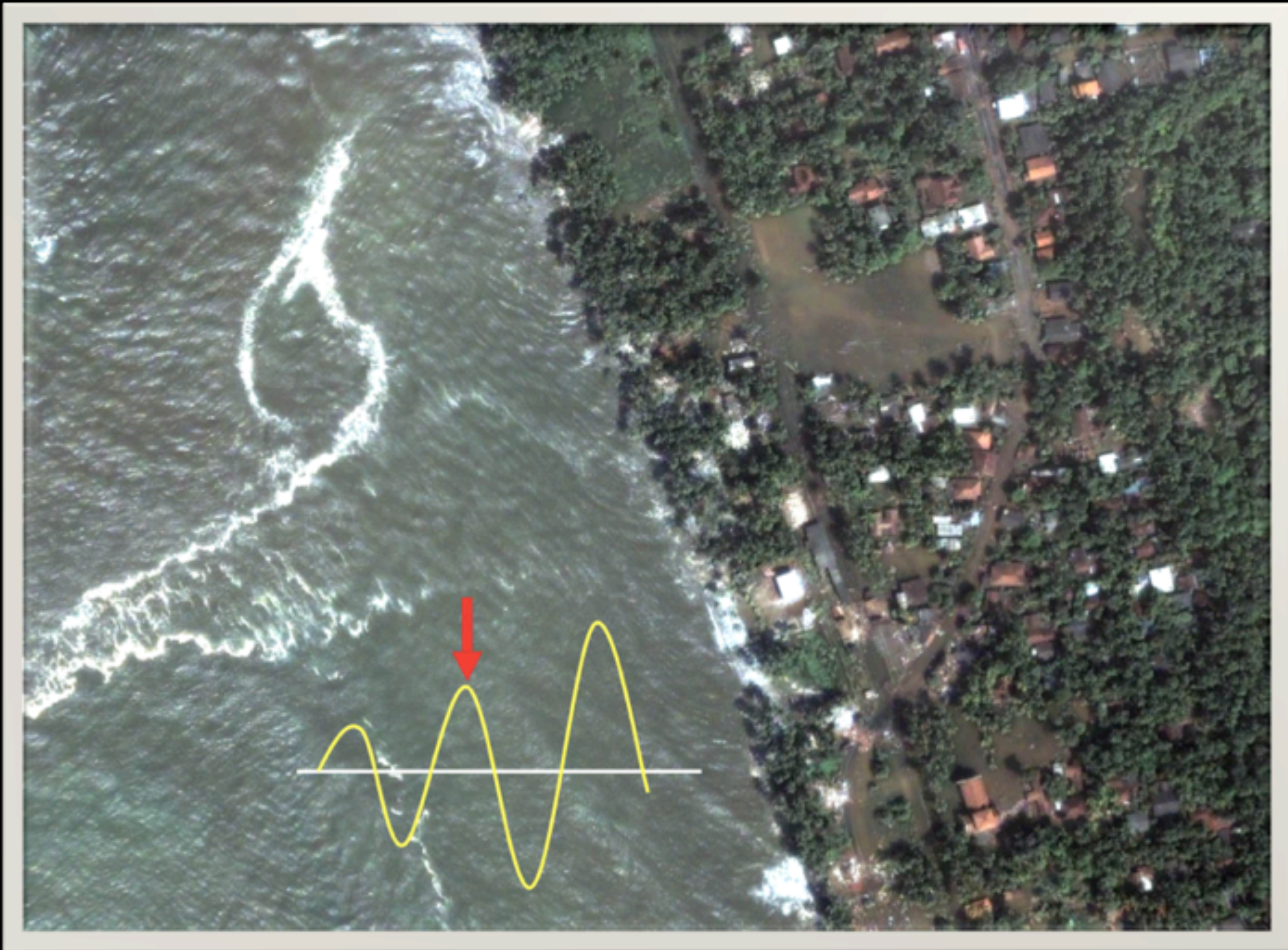
Kalutara, Sri Lanka, 2004
Quickbird satellite





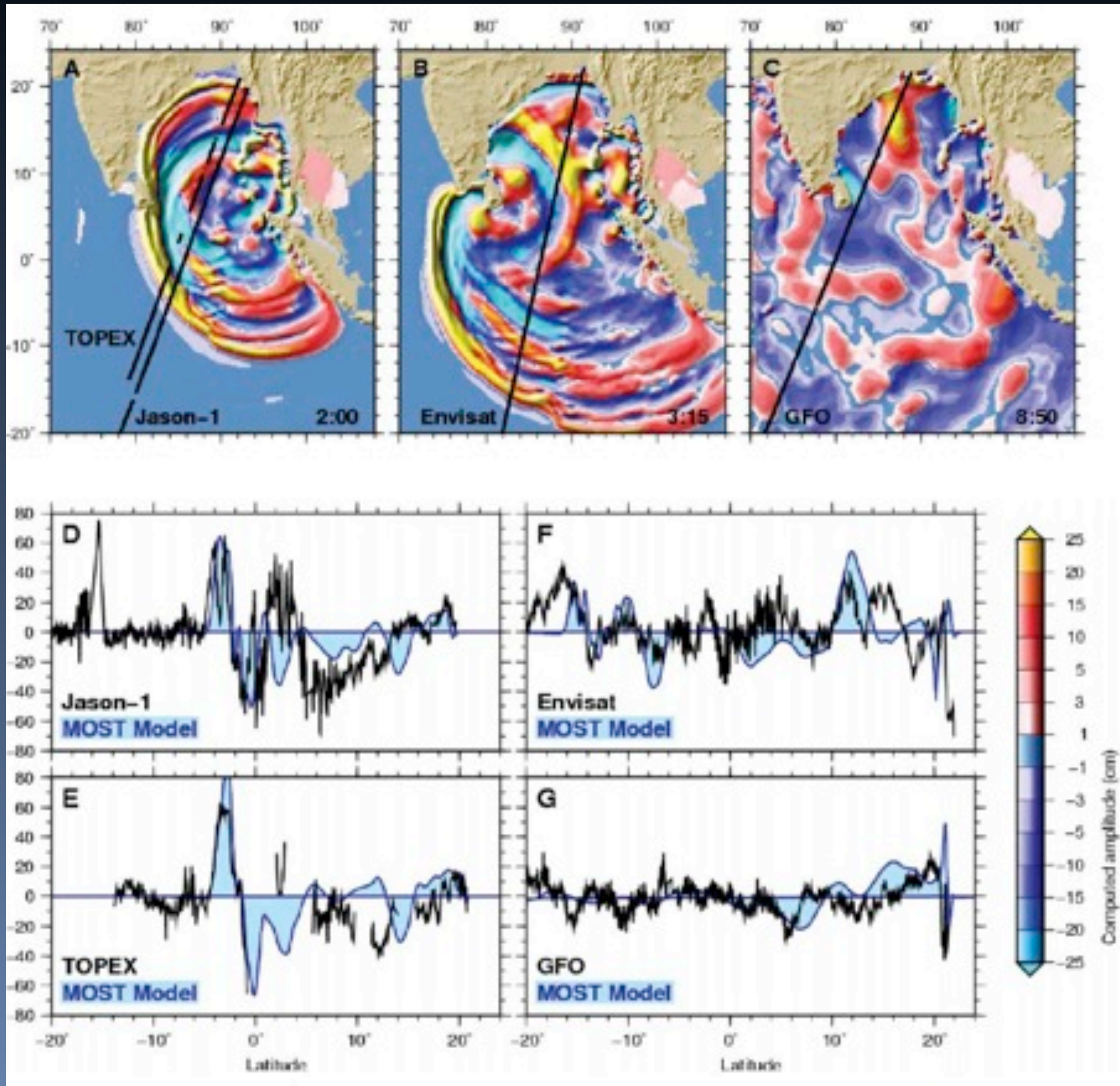
What can we do about forecasting Tsunamis?

- Deploy Detection Hardware.

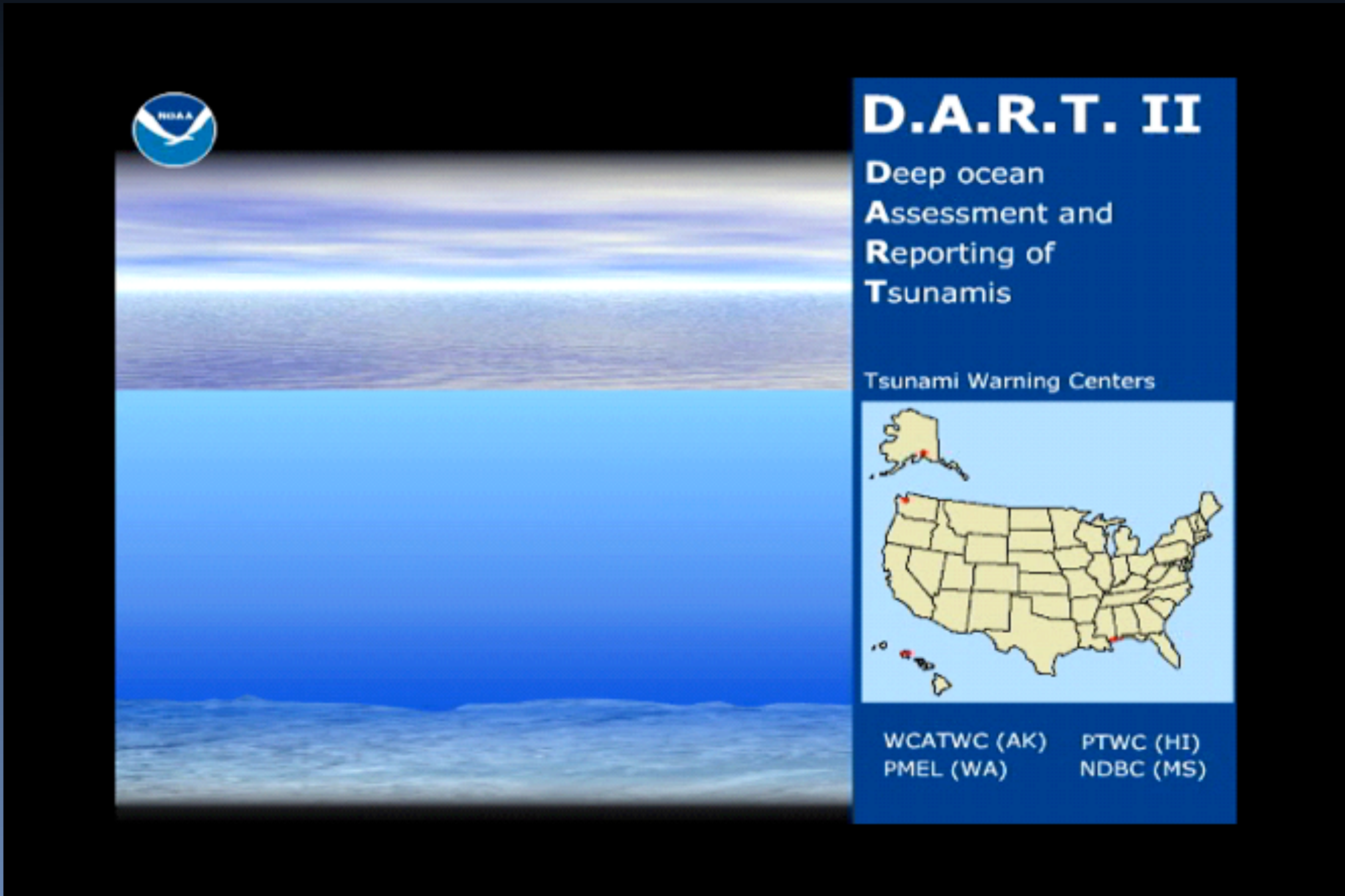
- Develop algorithms to interpret in-coming data.

- Develop numerical models to forecast/assess tsunami impact on the coast.

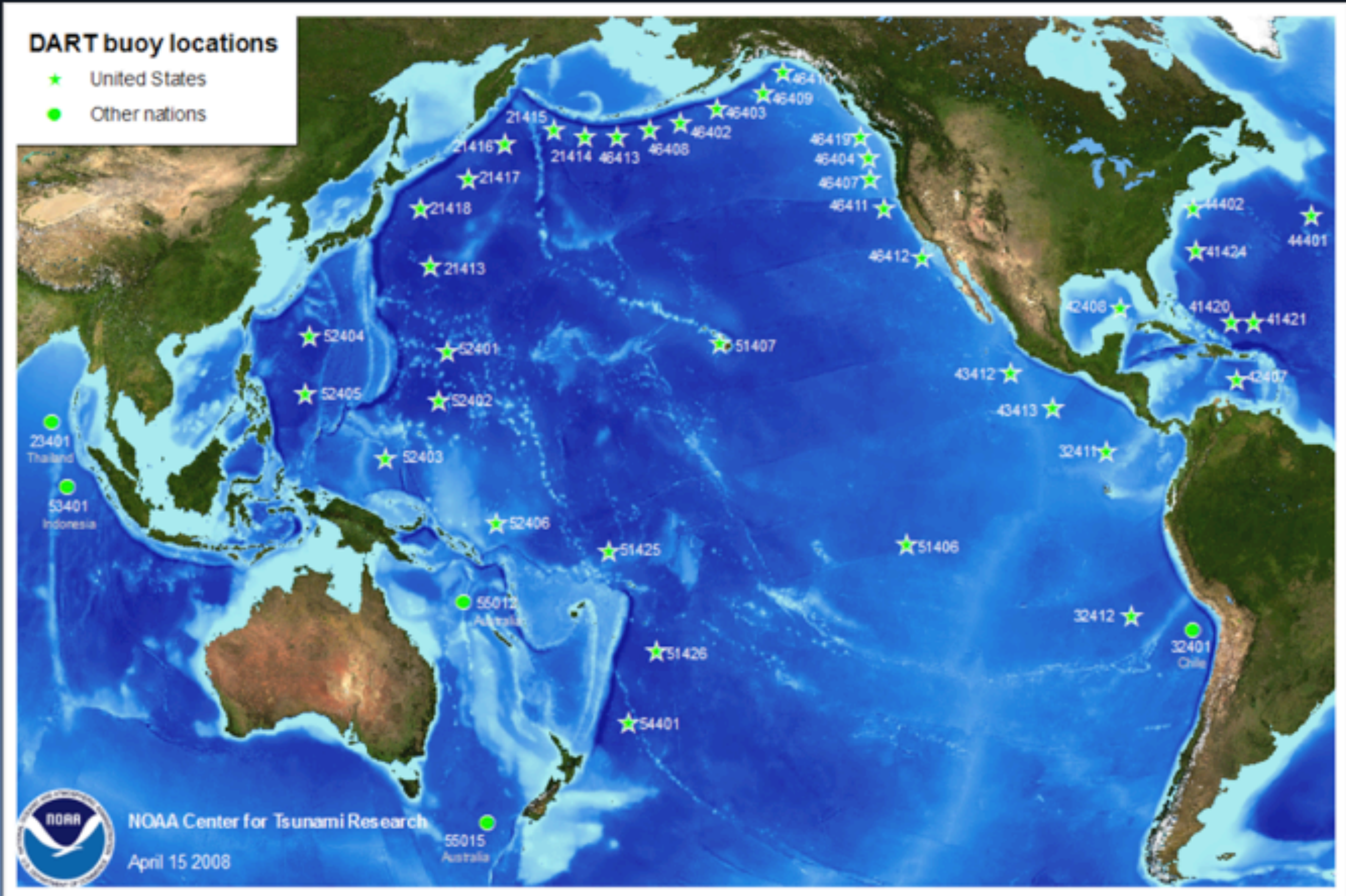
Tsunami Inversion based on satellite altimetry . Sumatra 2004 tsunami



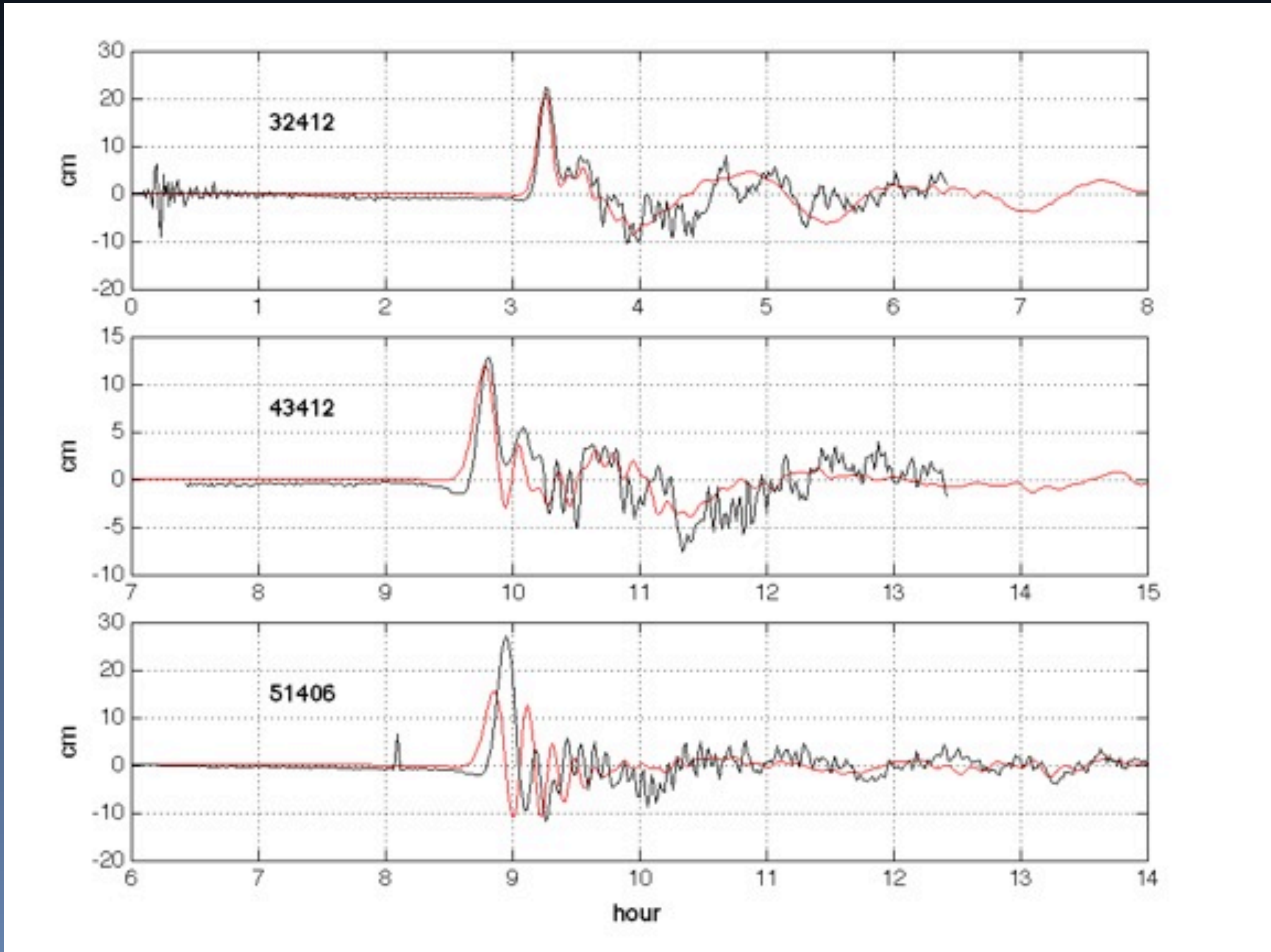
Tsunami Warning Systems: DART Systems



Dart Stations Position



DART time series Chile 2010 tsunami



- What do we constrain with the deep-water DART measurement?

```
Our deep-water propagation
model run database...
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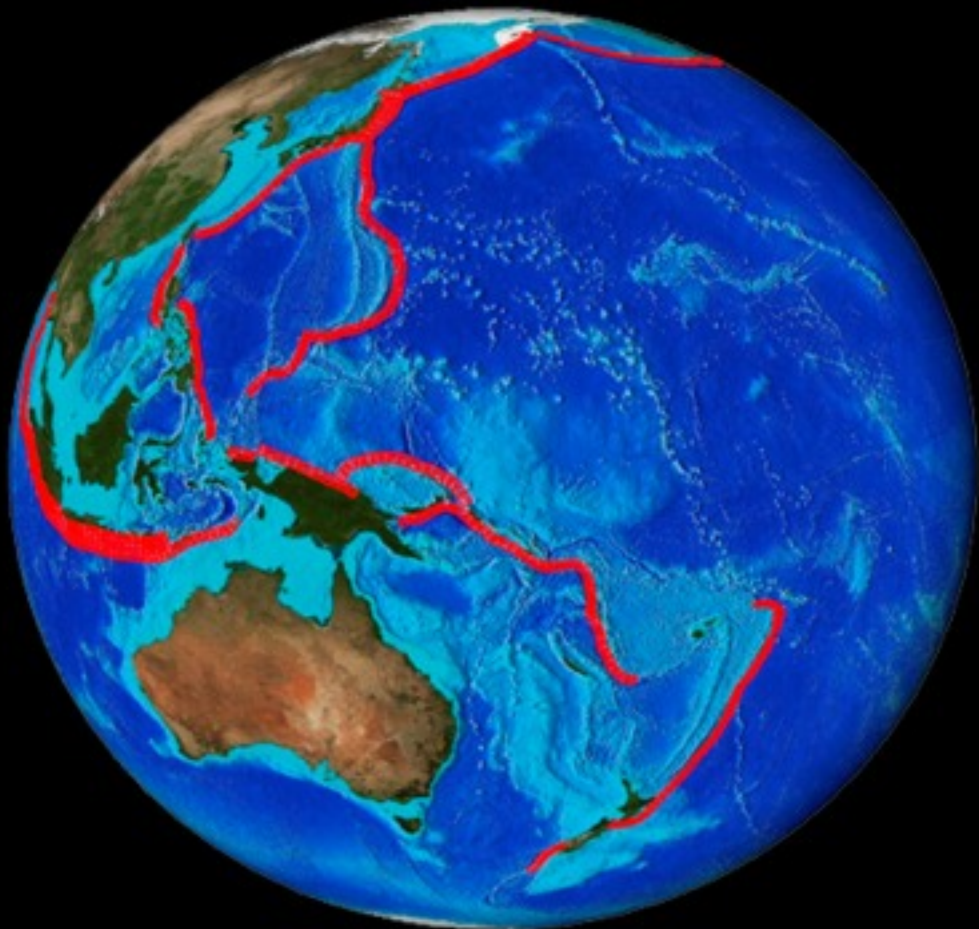
Locations of the unit sources for pre-computed tsunami events.



West Pacific

East Pacific

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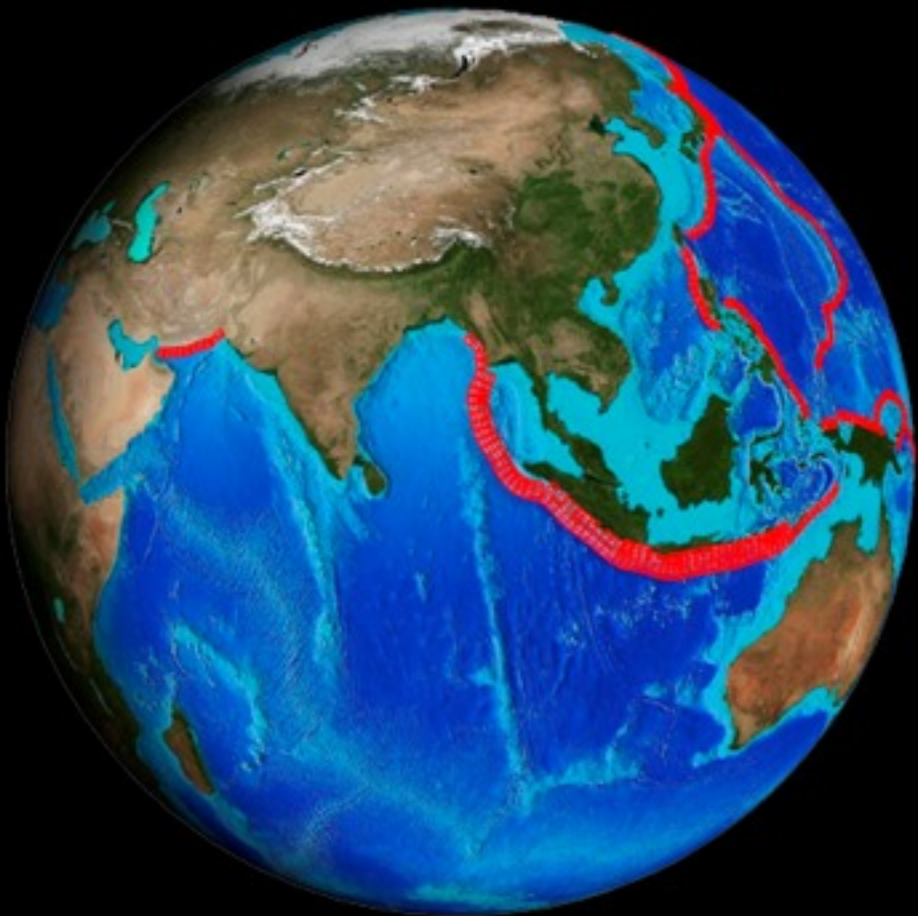


Indian Ocean

Atlantic Ocean

- Why can we just add arbitrary pre-run models together during a forecast?

Any combination of solutions to the linear equations of motion is also a solution:

Linearity...

Characteristic Form of the Non-linear Shallow Water Equations.

$$\begin{cases} h_t + (uh)_x = 0 \\ u_t + uu_x + gh_x = gd_x \\ v_t + uv_x = 0 \end{cases}$$

$$\begin{aligned} p_t + \lambda_1 p_x &= gd_x \\ q_t + \lambda_2 q_x &= gd_x \\ v'_t + \lambda_3 v'_x &= 0 \end{aligned}$$

Riemann invariants

$$\begin{aligned} p &= u + 2\sqrt{gh} \\ q &= u - 2\sqrt{gh} \\ v' &= v \end{aligned}$$

Eigenvalues

$$\begin{aligned} \lambda_1 &= u + \sqrt{gd} \\ \lambda_2 &= u - \sqrt{gd} \\ \lambda_3 &= u \end{aligned}$$

In deep water the equations are linear!!
We can do propagation database!!

Deep-Water Linearity

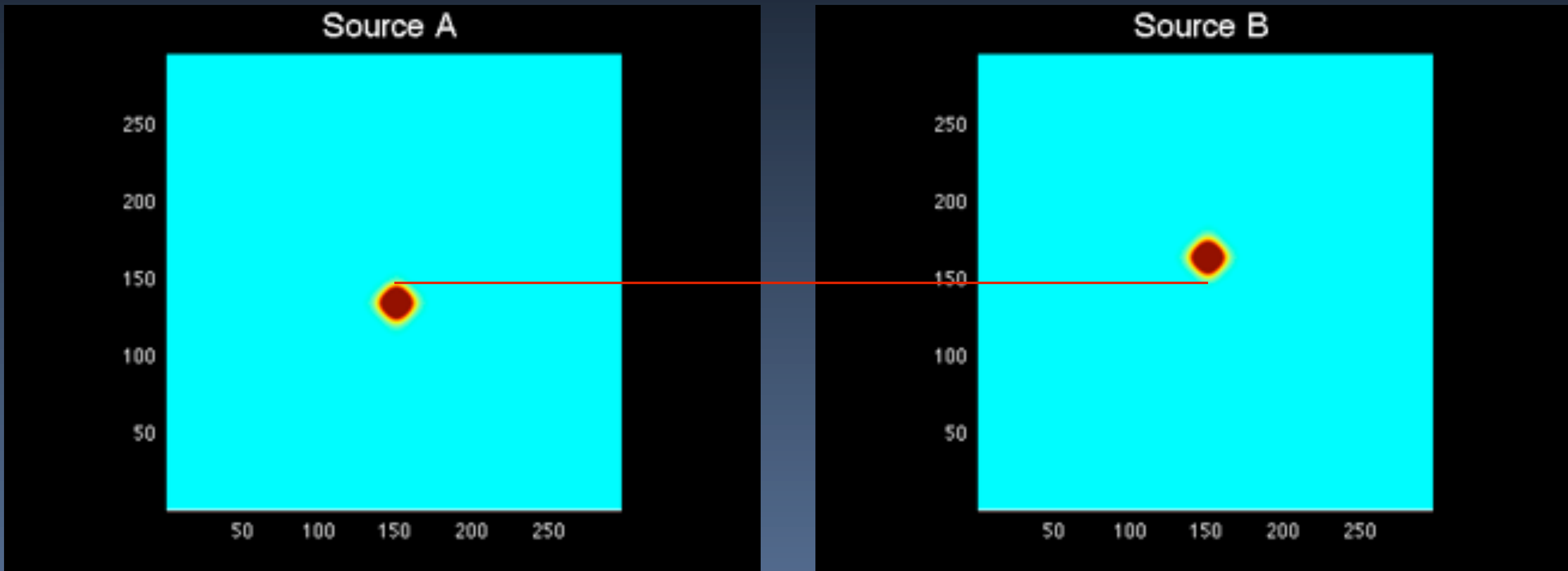
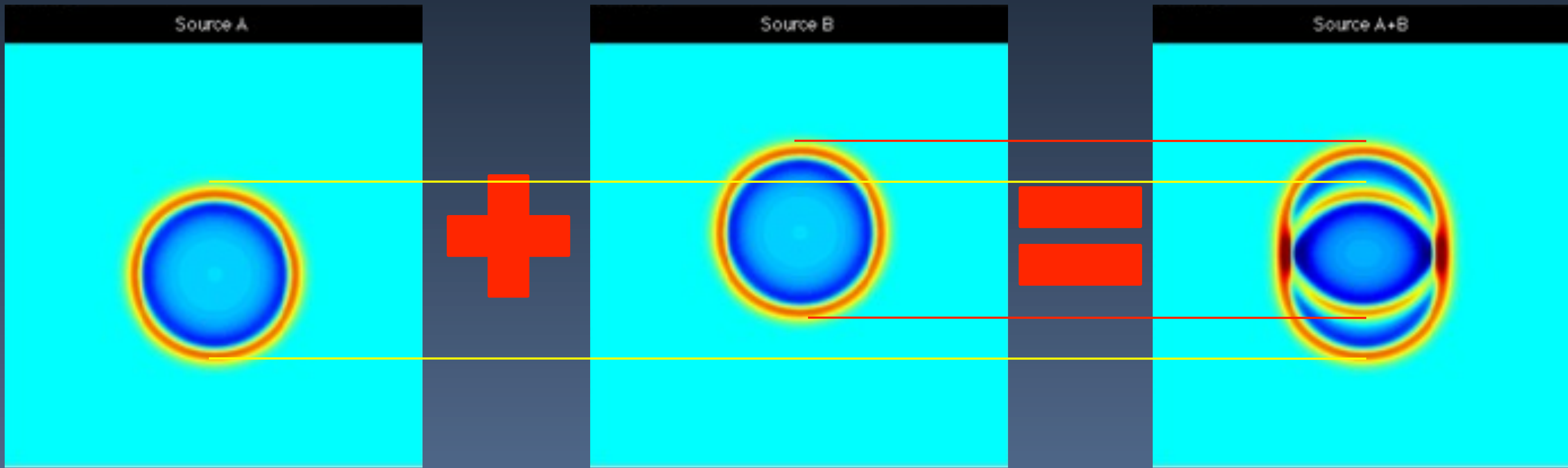


Illustration of Deep Water Linearity



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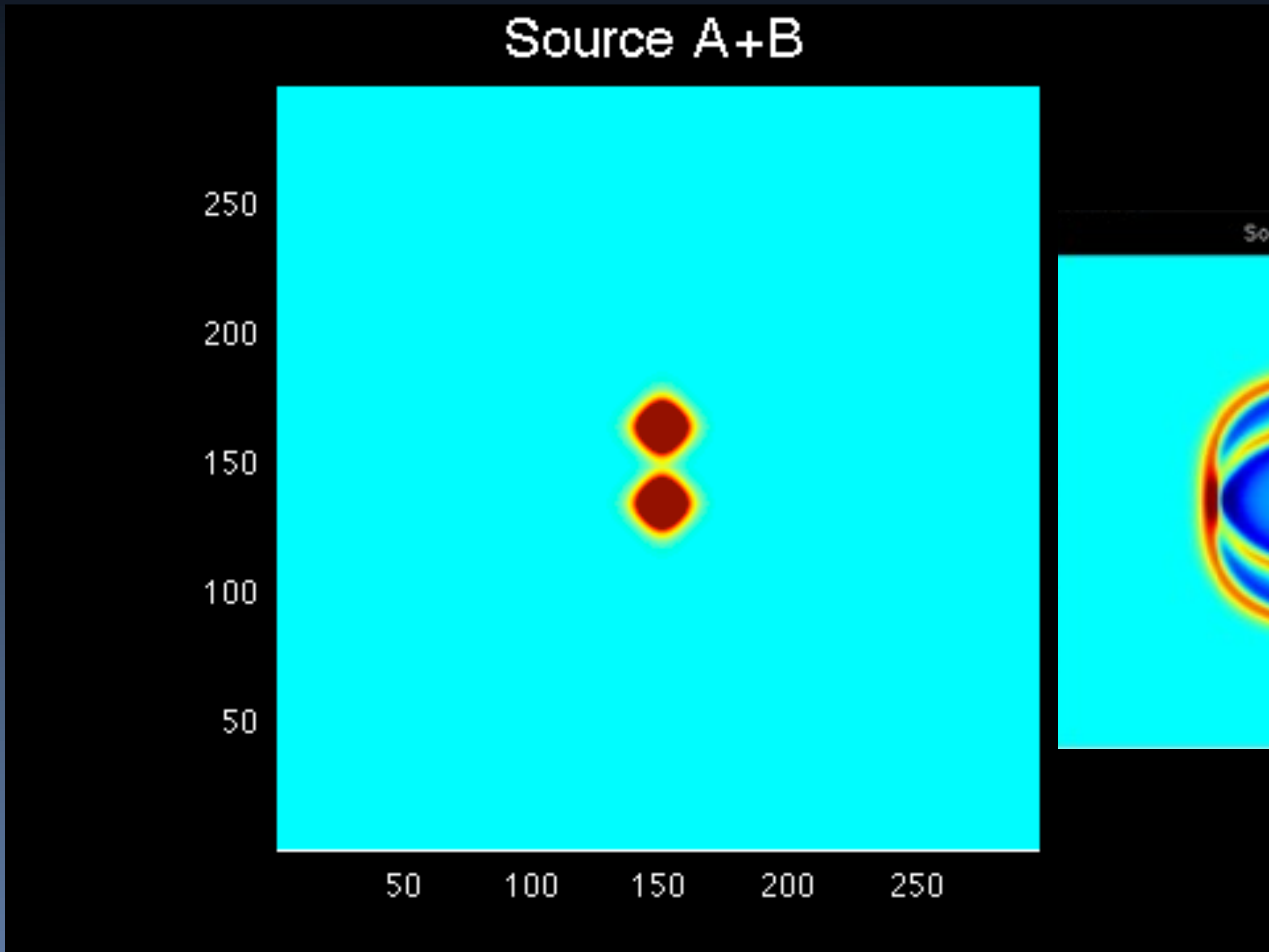
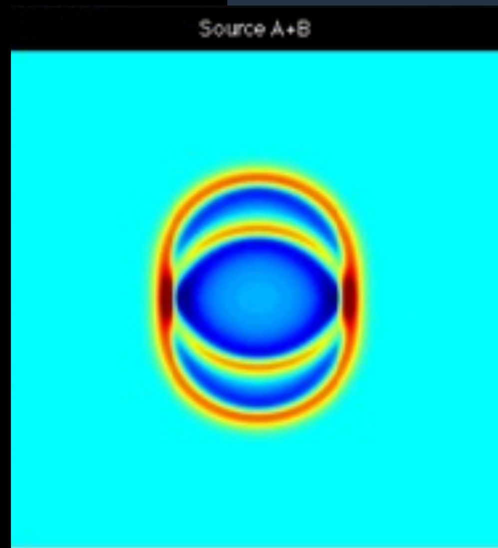
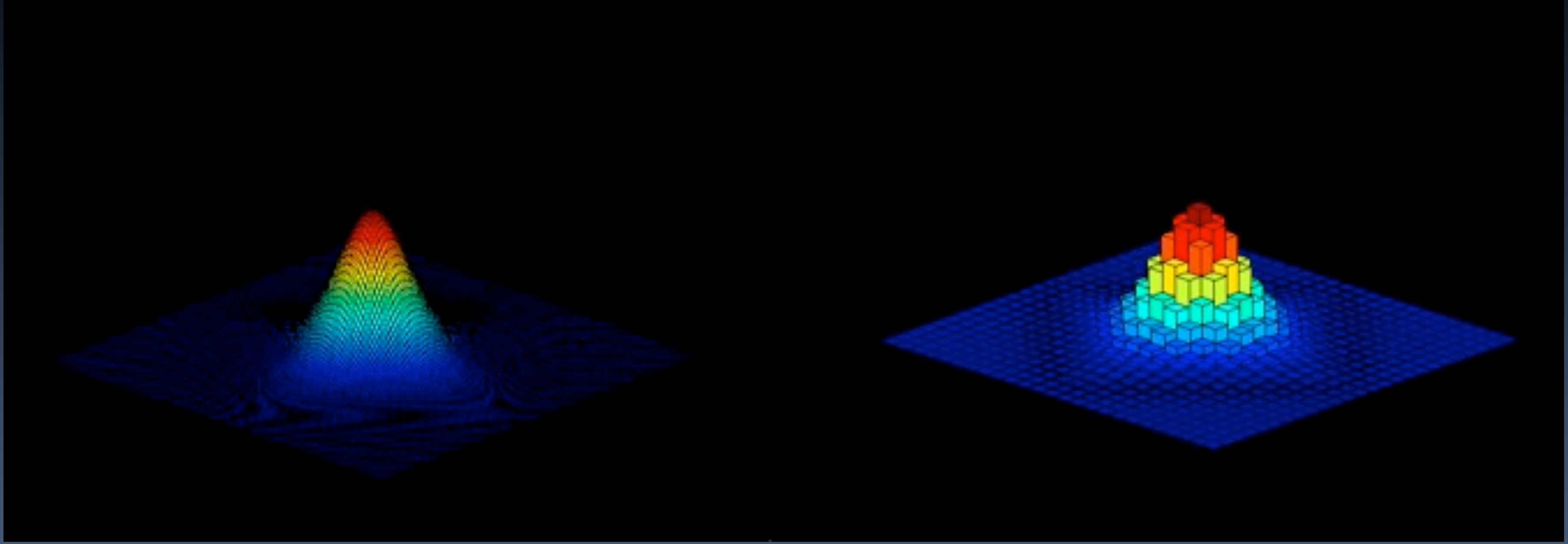


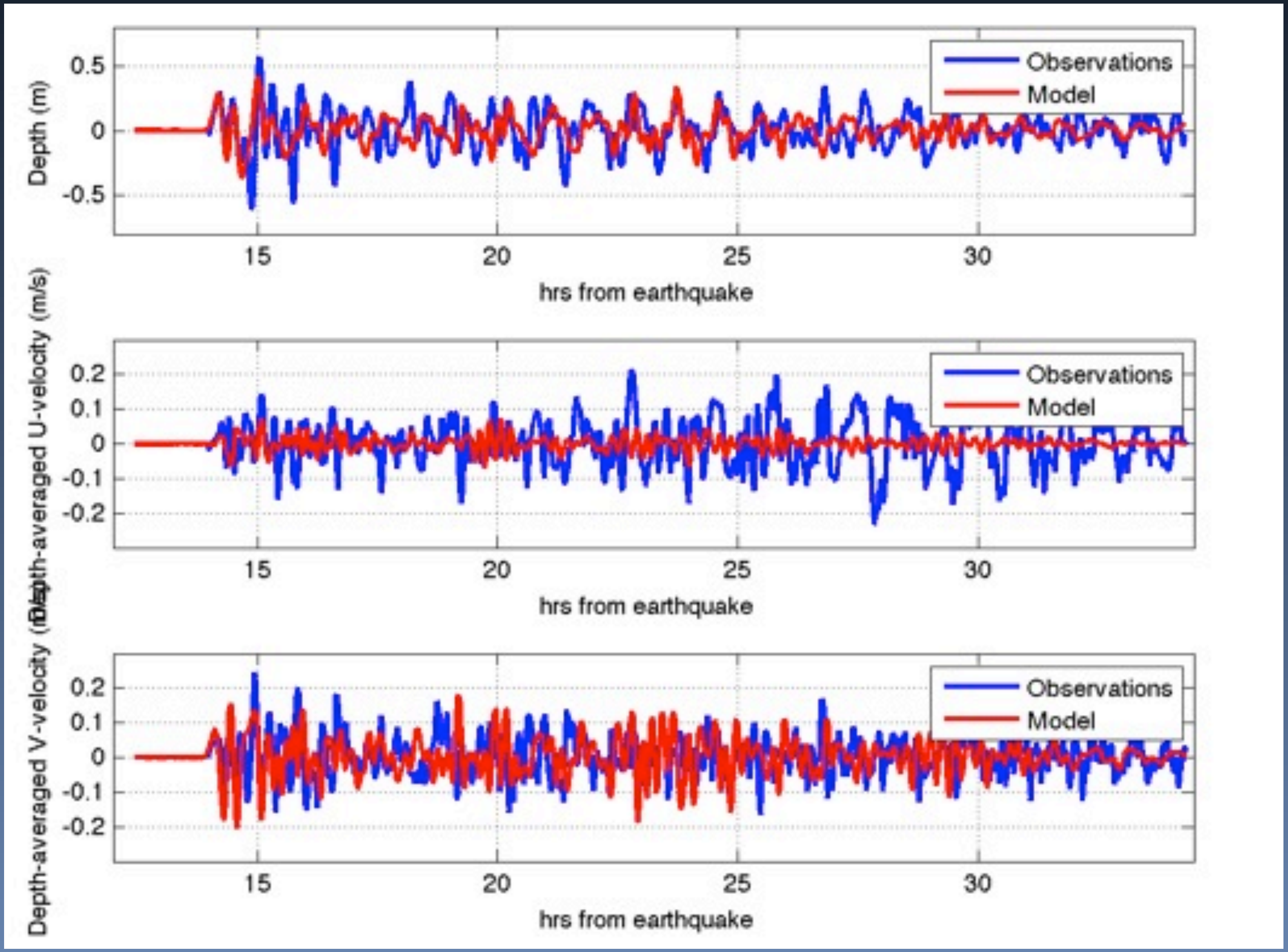


Linearity allows for the reconstruction of an arbitrary tsunami sources using elementary building blocks



For linearity u << gh

$$\sqrt{0.1^2 + 0.1^2} << \sqrt{9.8 \times 10}$$



- We know the deep-water tsunami obeys linear equations of motion
- We have many, many pre-run deep-water model runs in a "Propagation Database"

`How do we produce the right combination during an event?`

Inversion

- WebSIFT demo
- http://sift.pmel.noaa.gov/websift

Break

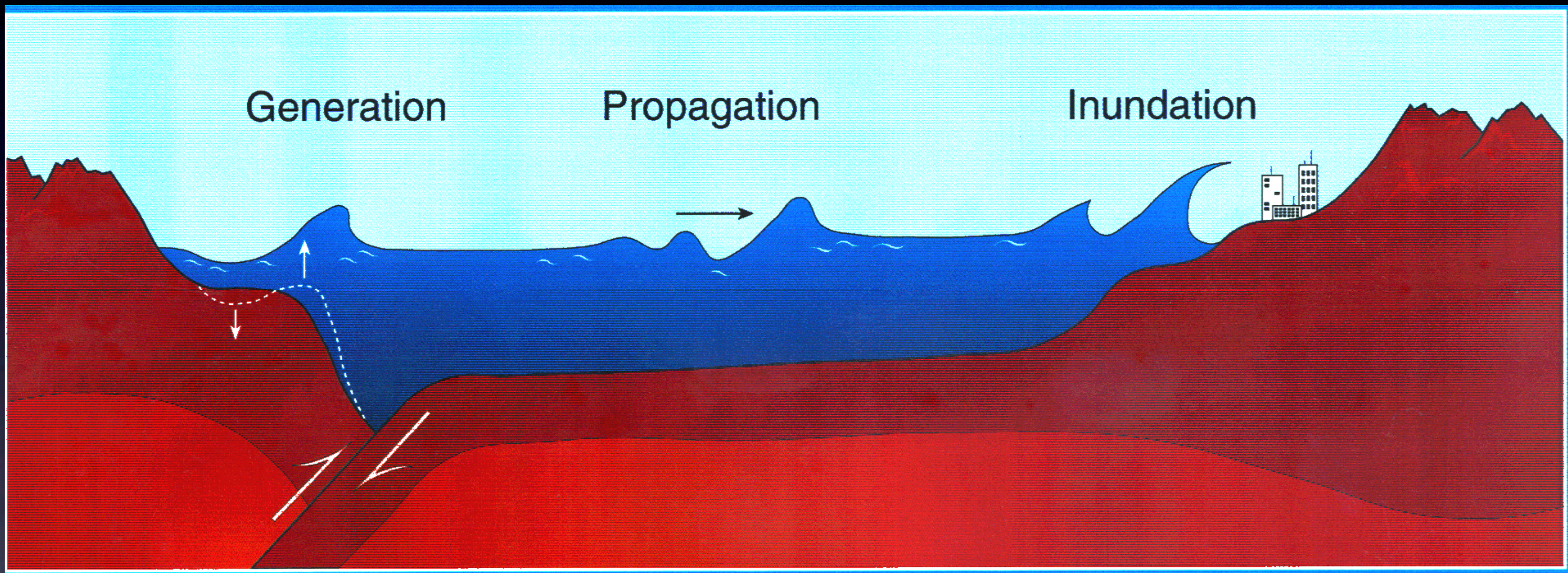
- Now we have the “best-fit” deep-water propagation run…
- How do we get the solution to the harbor?

Inundation...

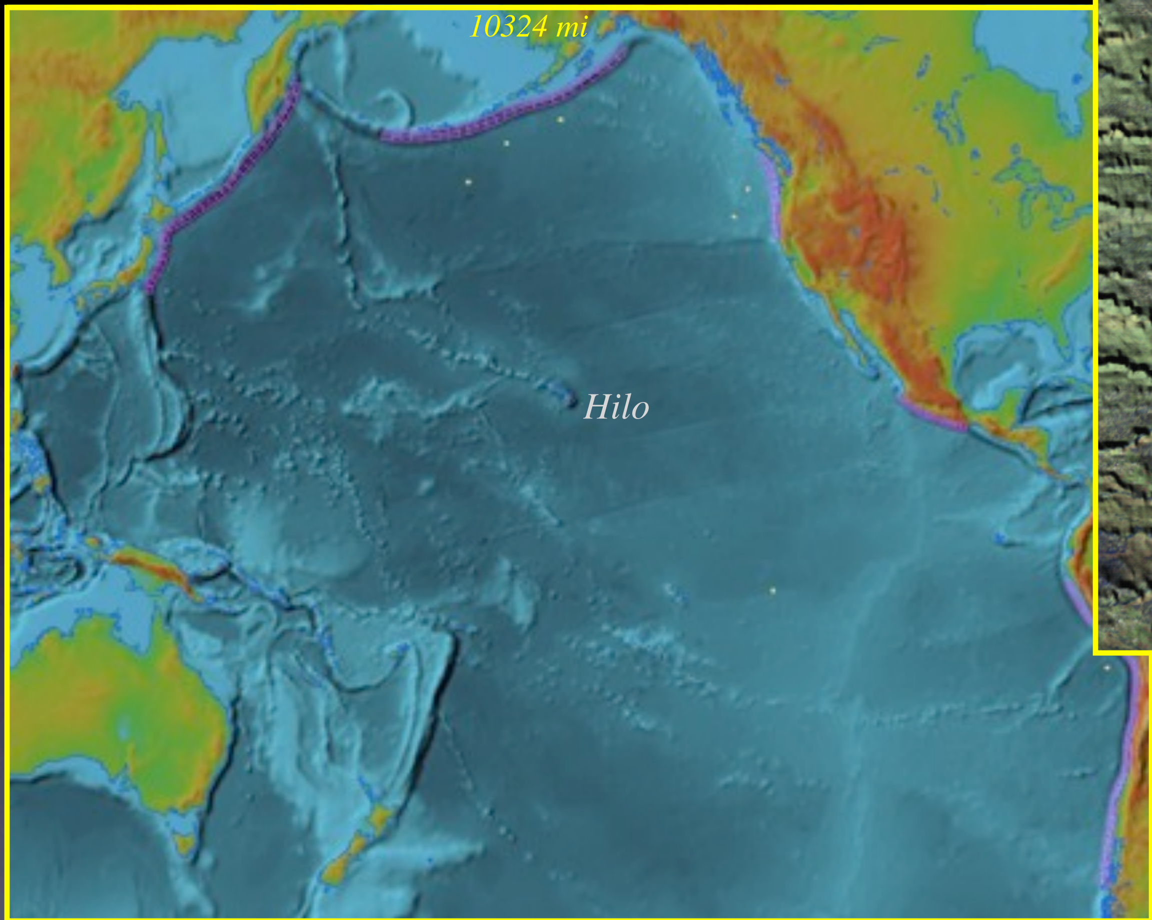
Inundation: 3 telescoping grids

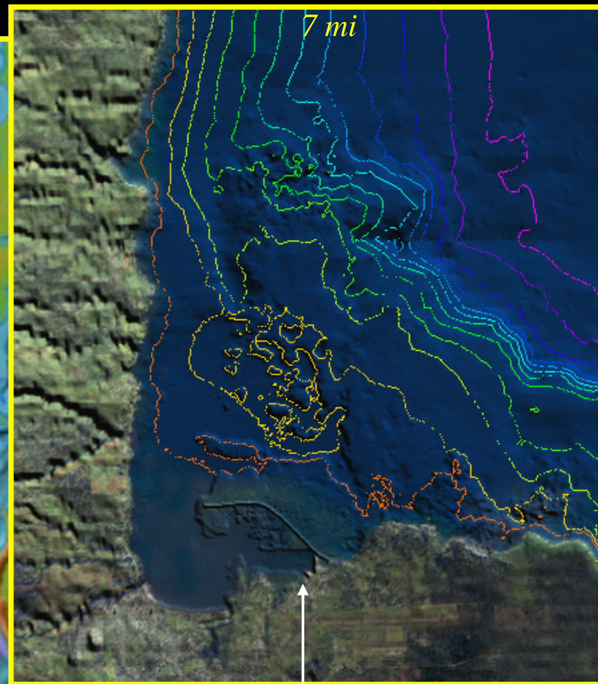
- 3 nested grids used to model the shoaling wave evolution from deep-water to shallow bay, harbor, or coastline
- optimized to run quickly
- takes forcing from linearly-combined, pre-run Propagation model output

Why model separately?



Reason 1 : Different scales





Location of Hilo tide-gage

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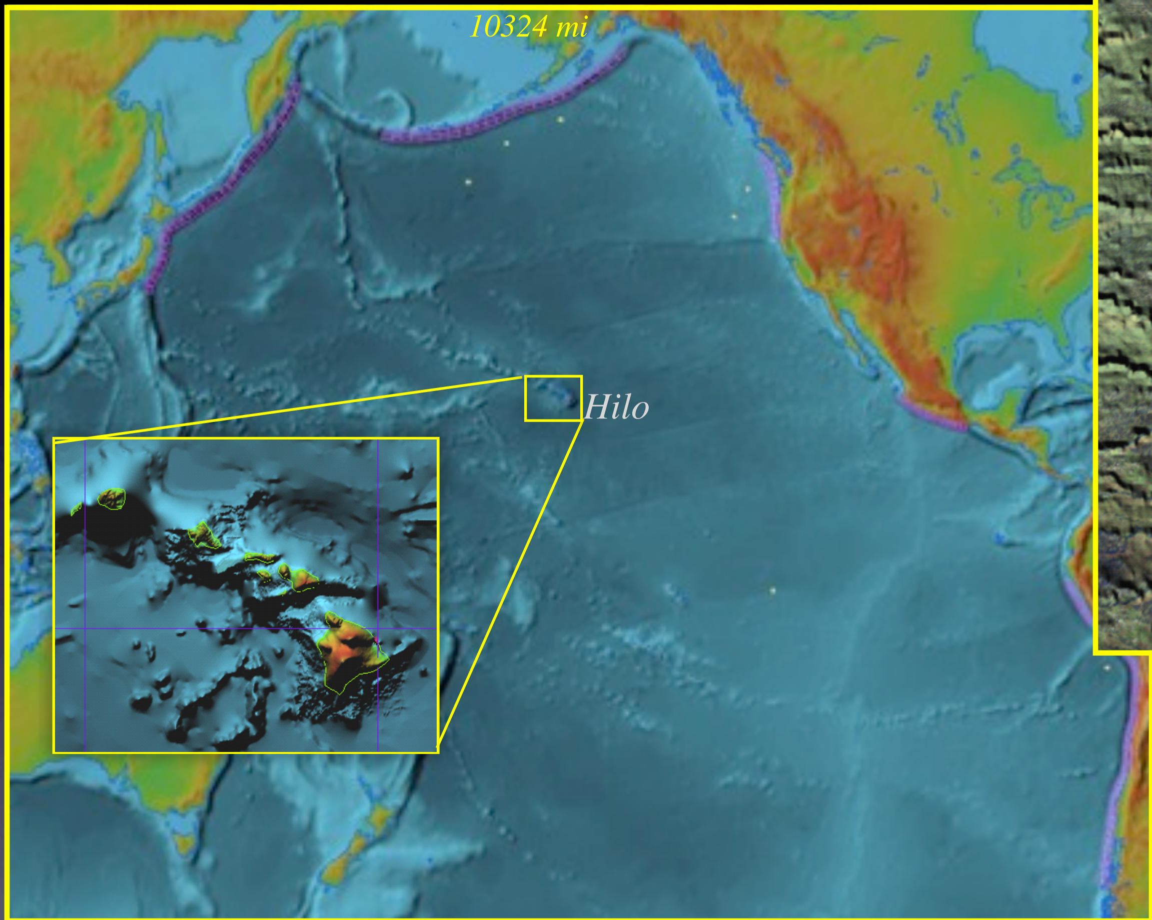

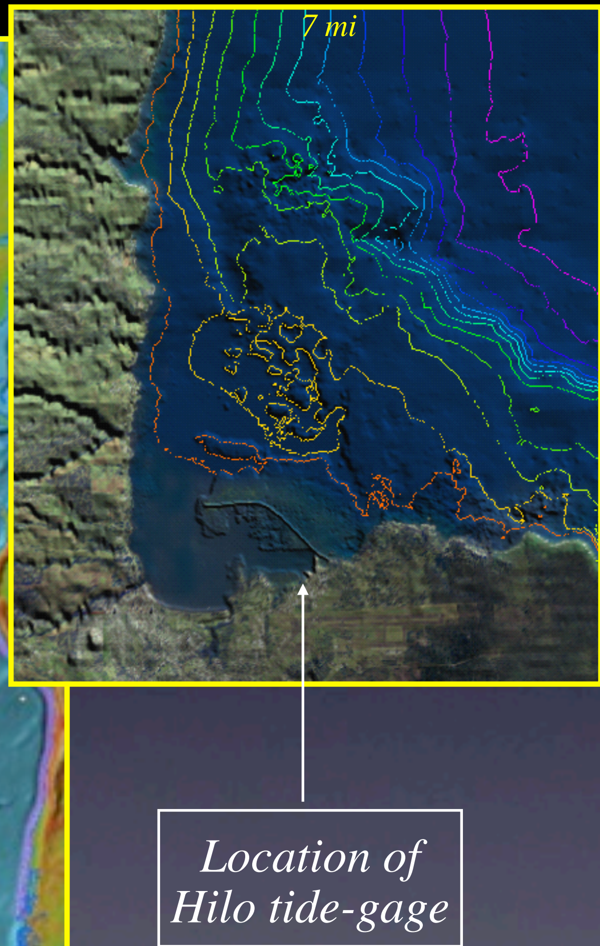

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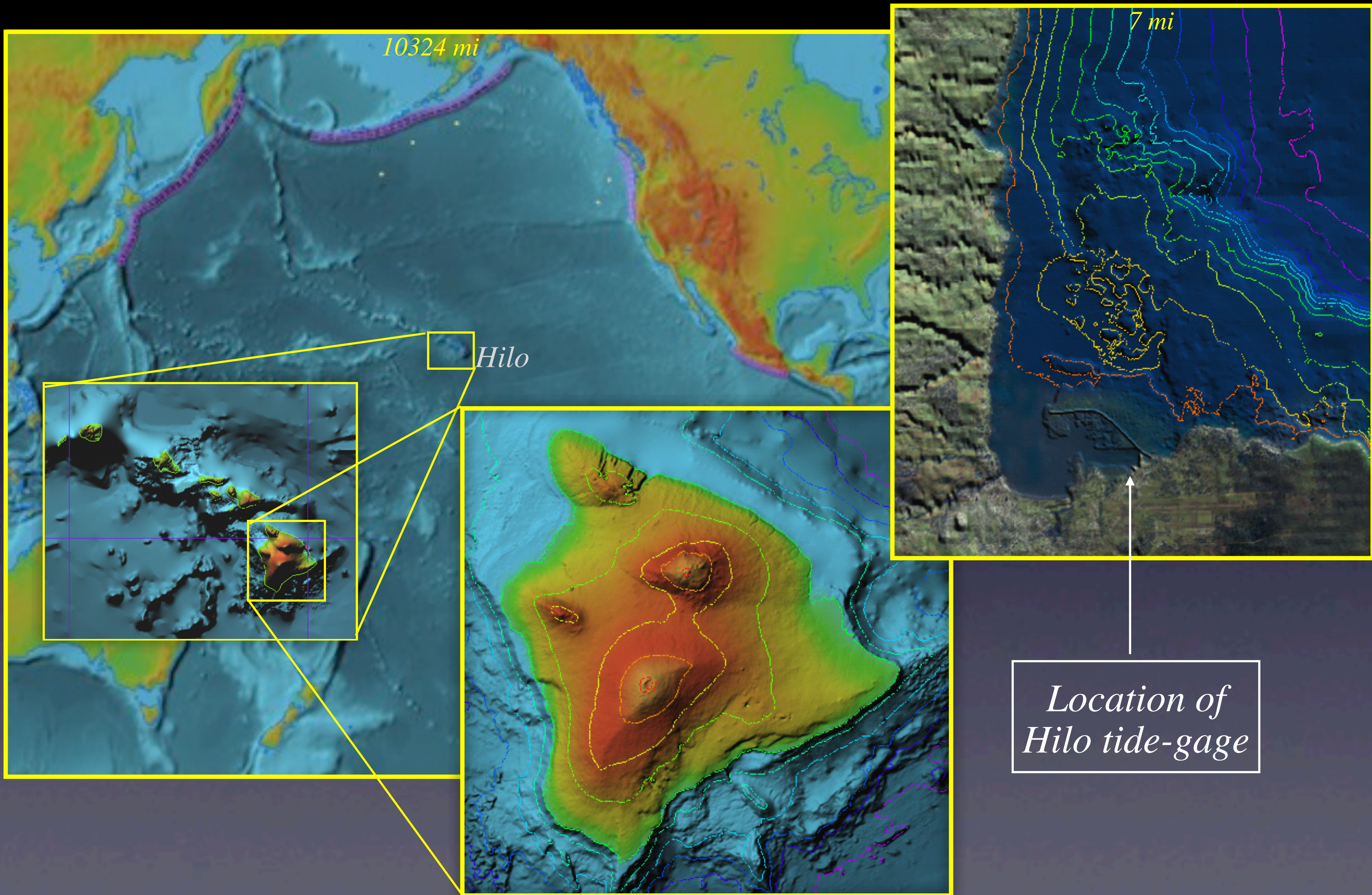

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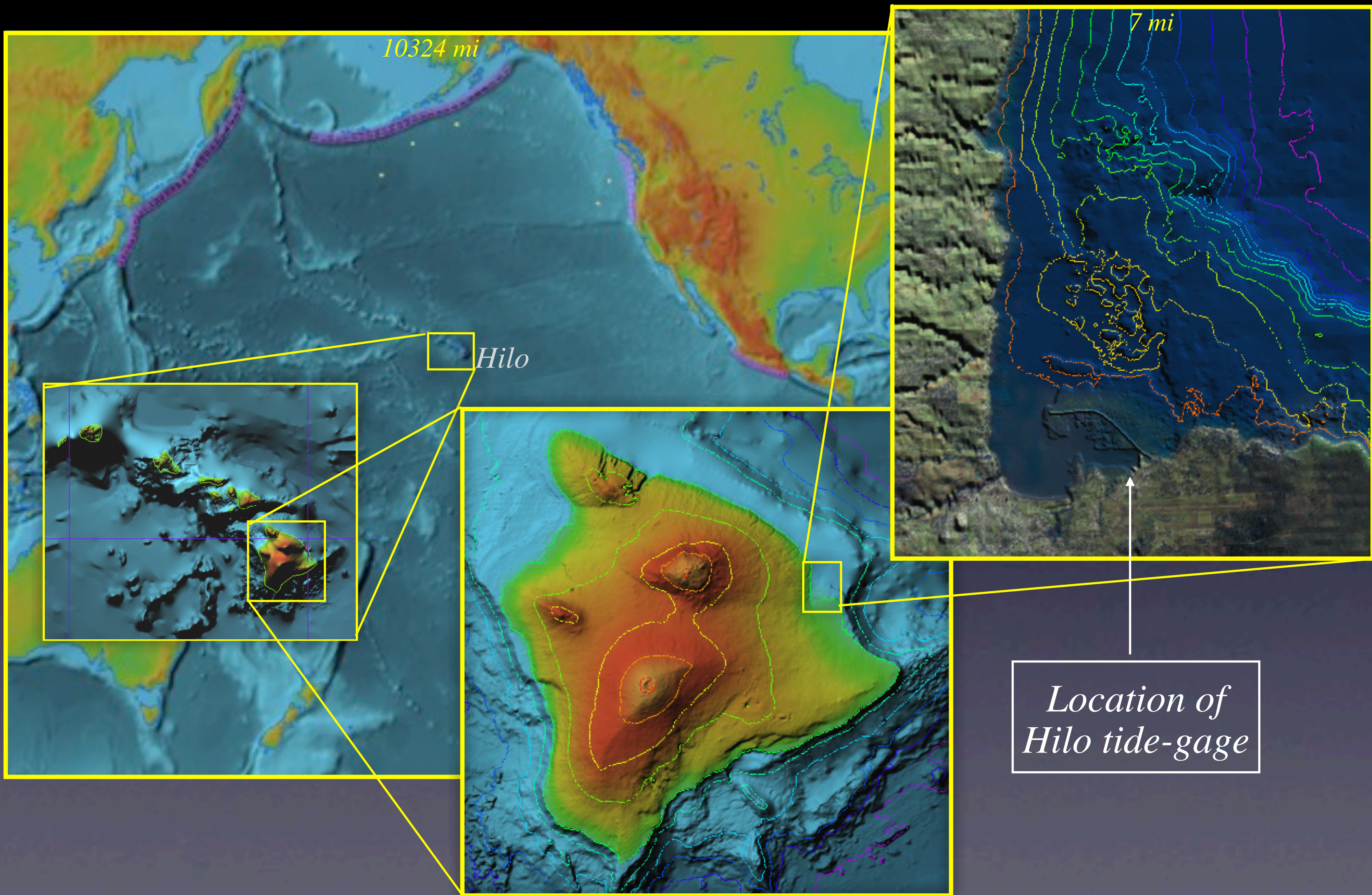
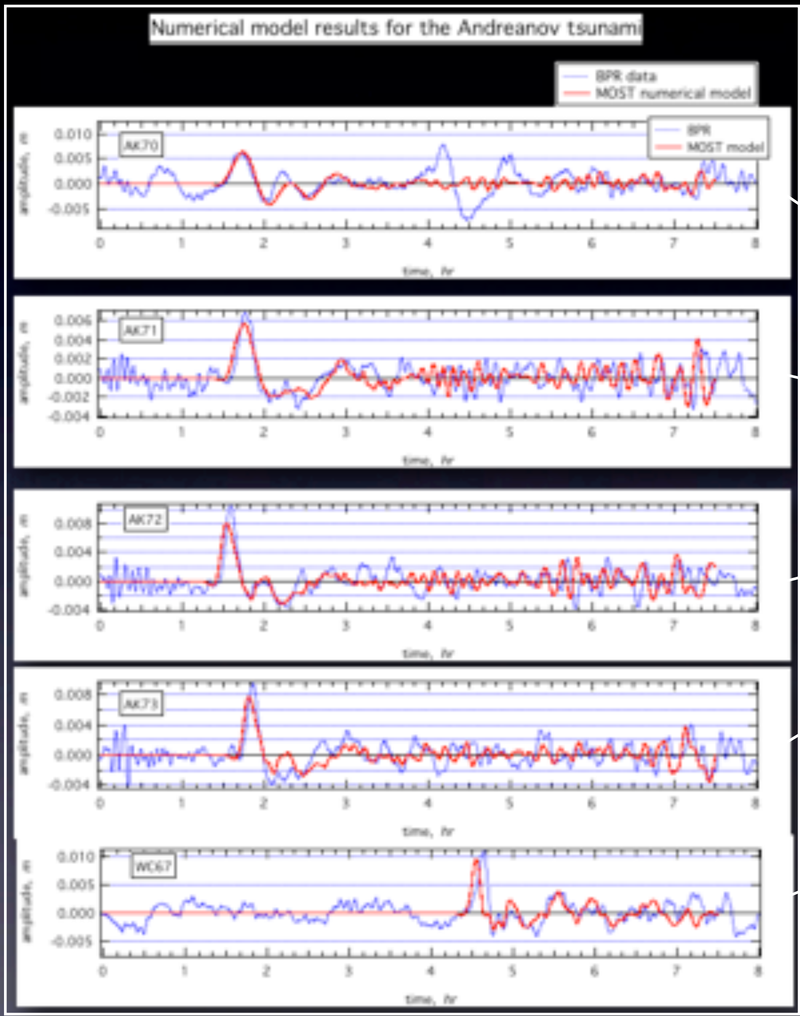
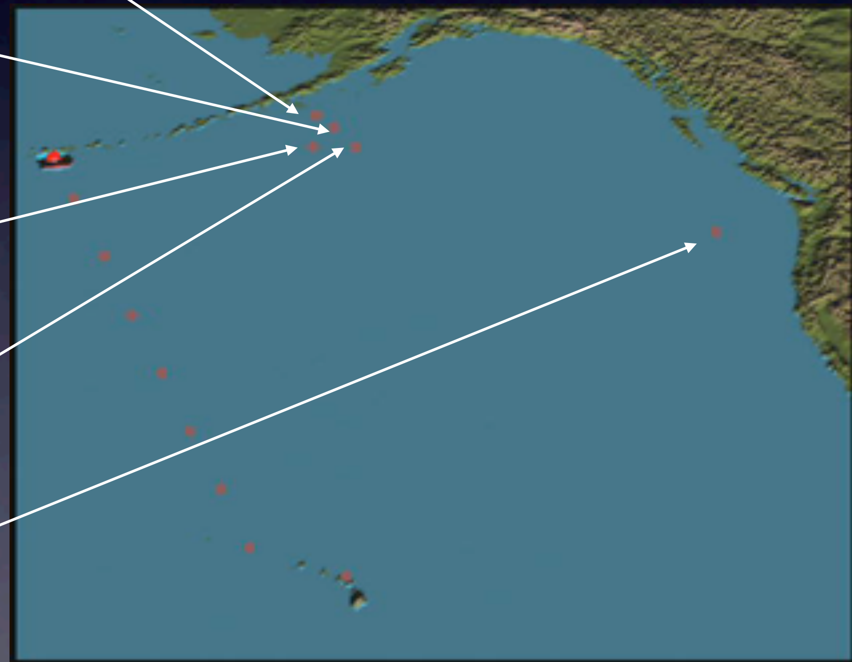


Propagation scale

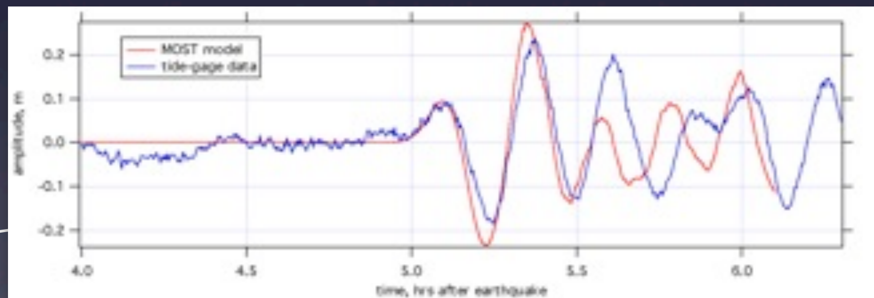


June 10, 1996 Andreanov tsunami
(Titov & Gonzalez, 1997)

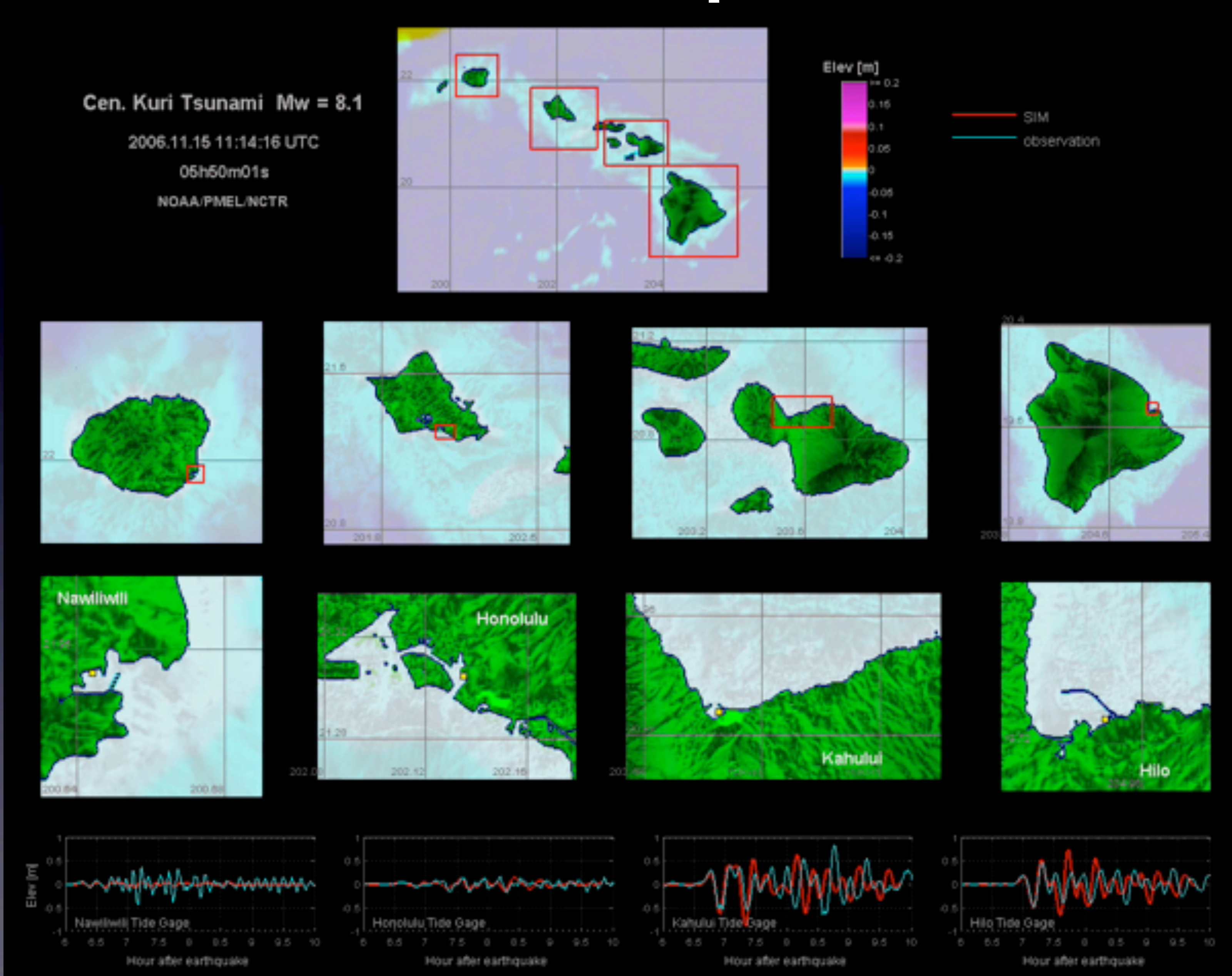


Inundation model scale

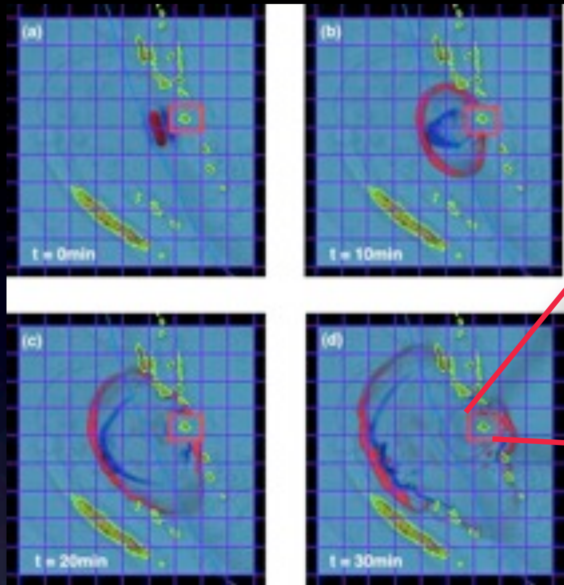
Andreanov tsunami “inundation” model comparison with tide-gage data

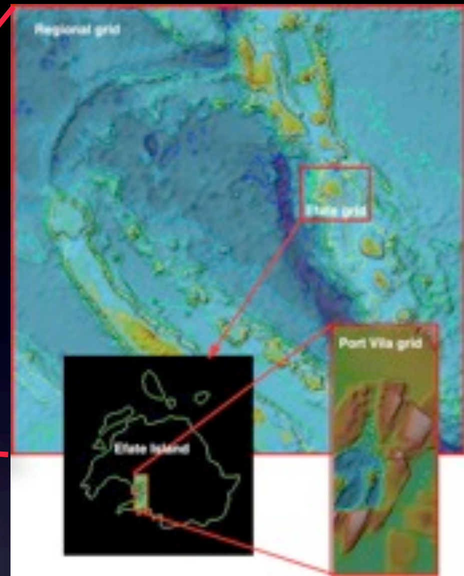


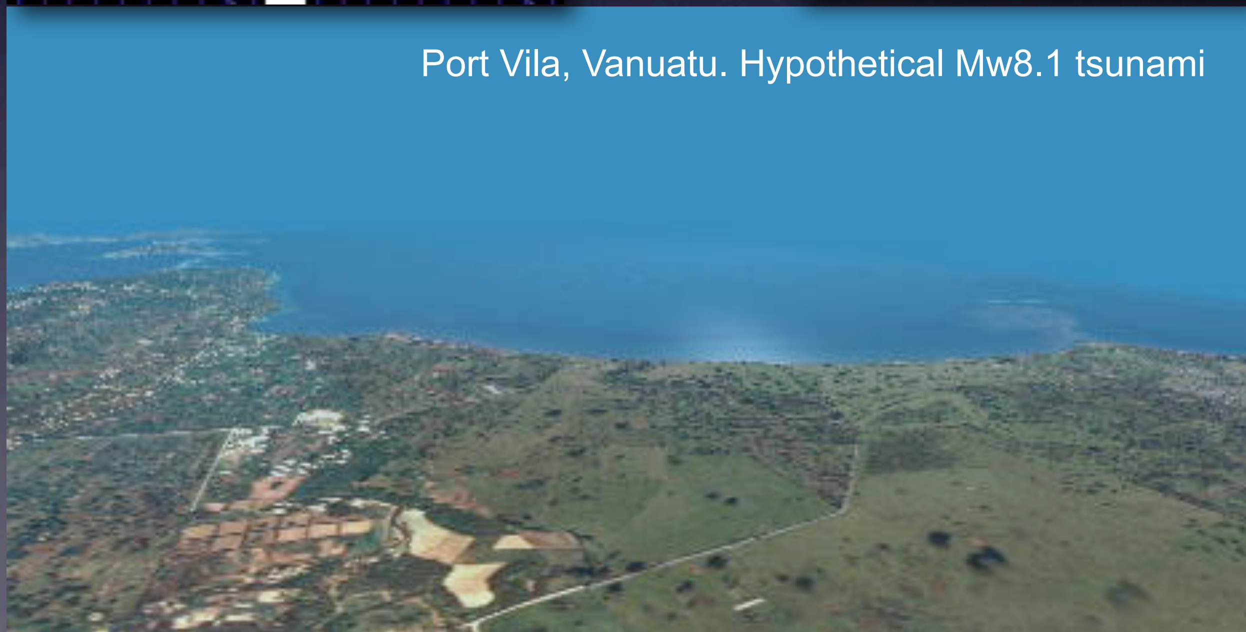
Scale comparison



Small scale inundation effects





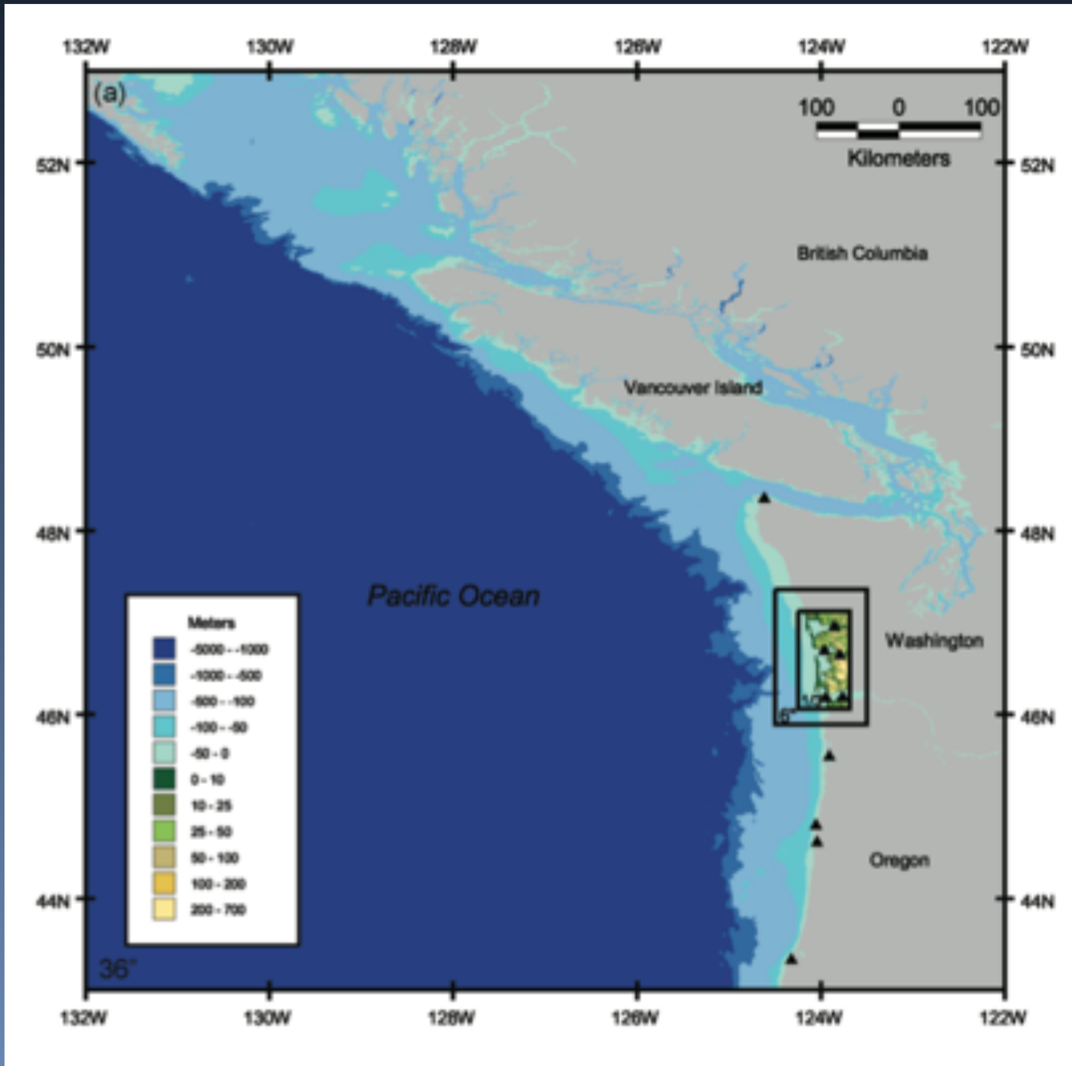


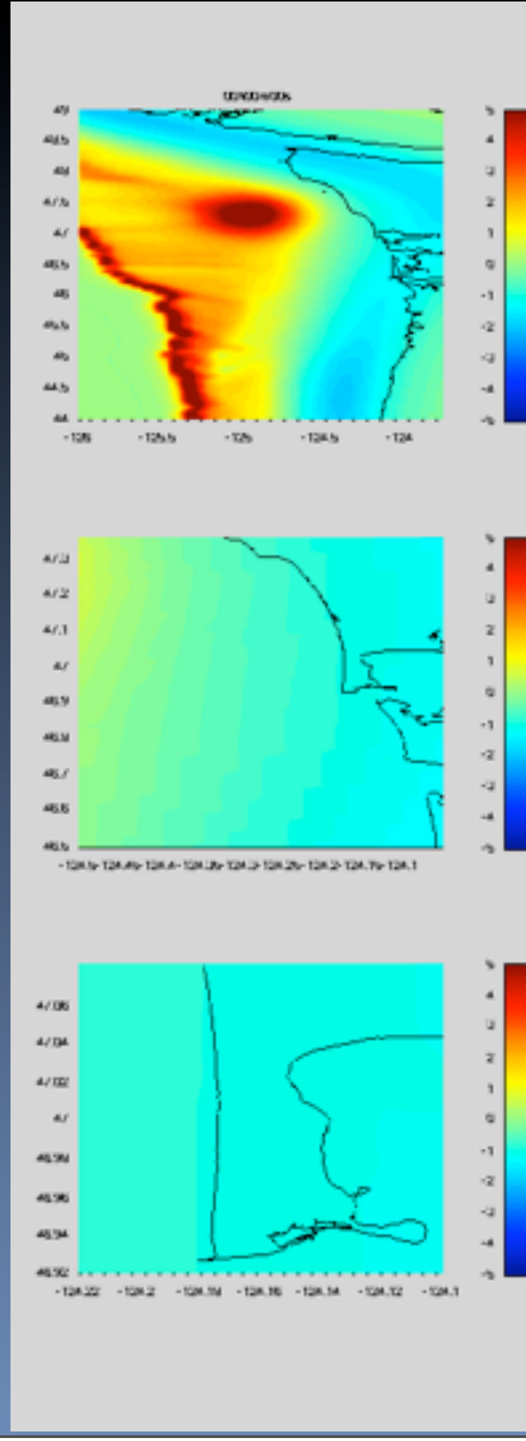
Reason 2: Inundation dynamics

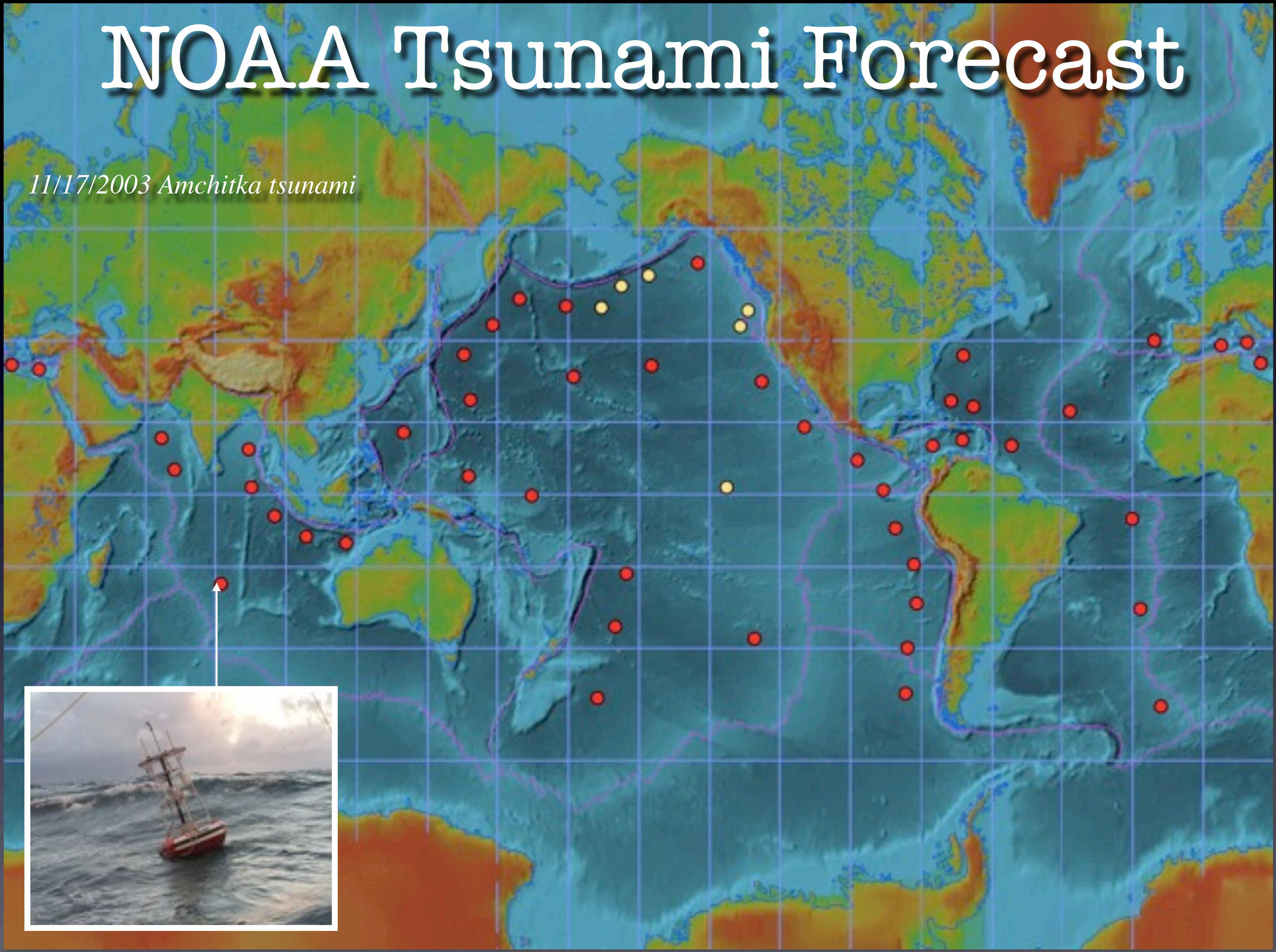
Simulation of the Aonae inundation

(1993 Okushiri tsunami)

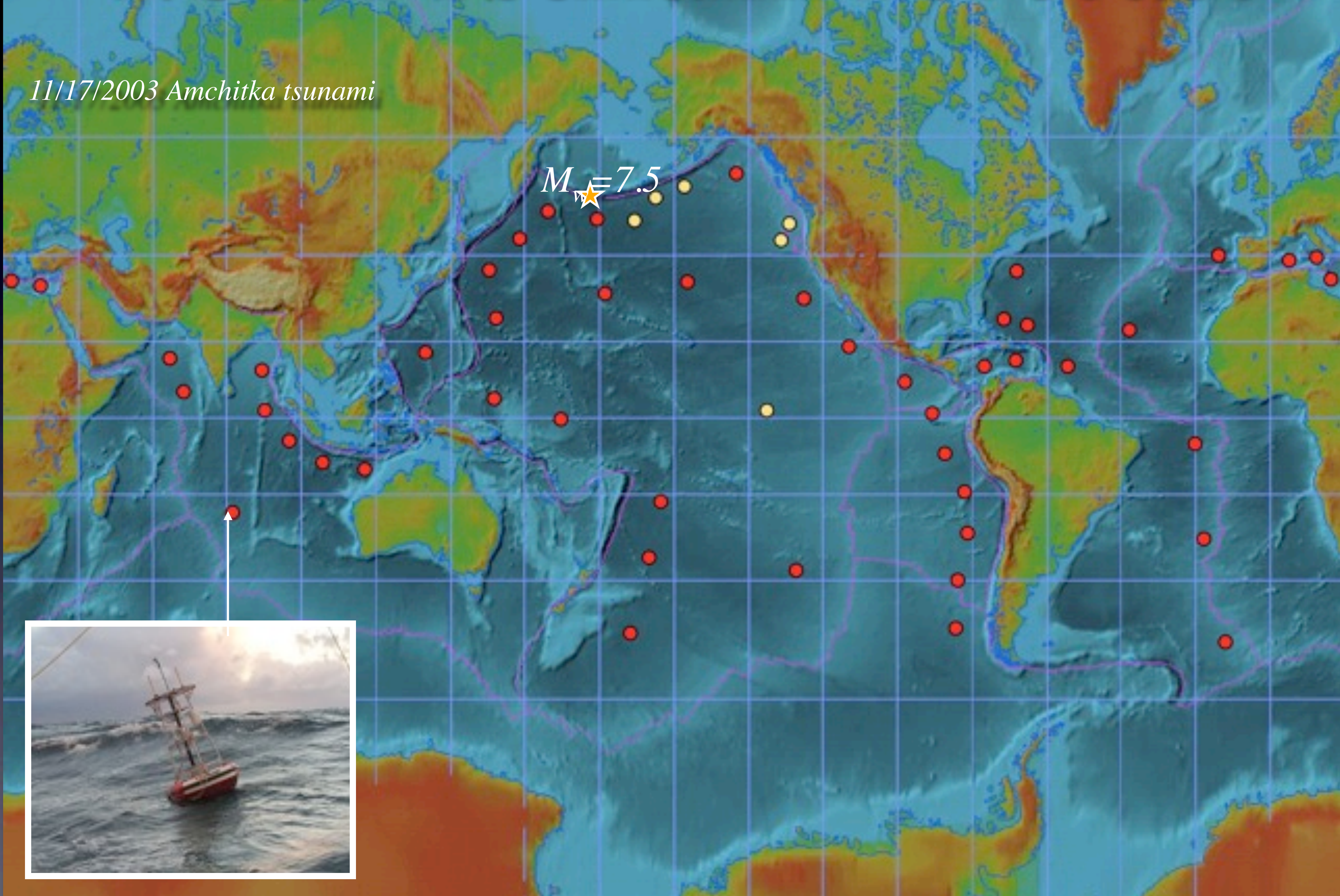
Tsunami Forecast for Ocean Shores, WA



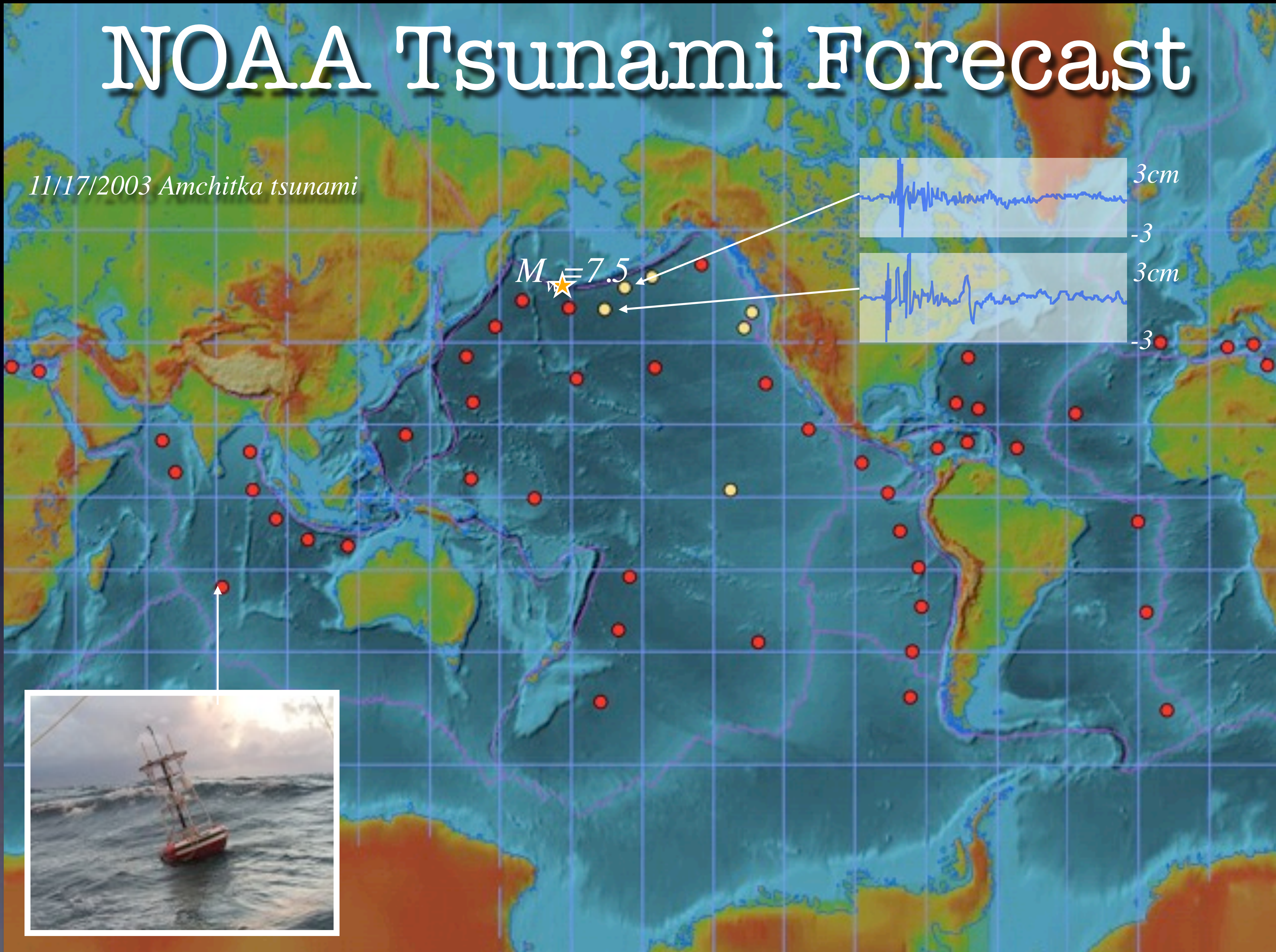


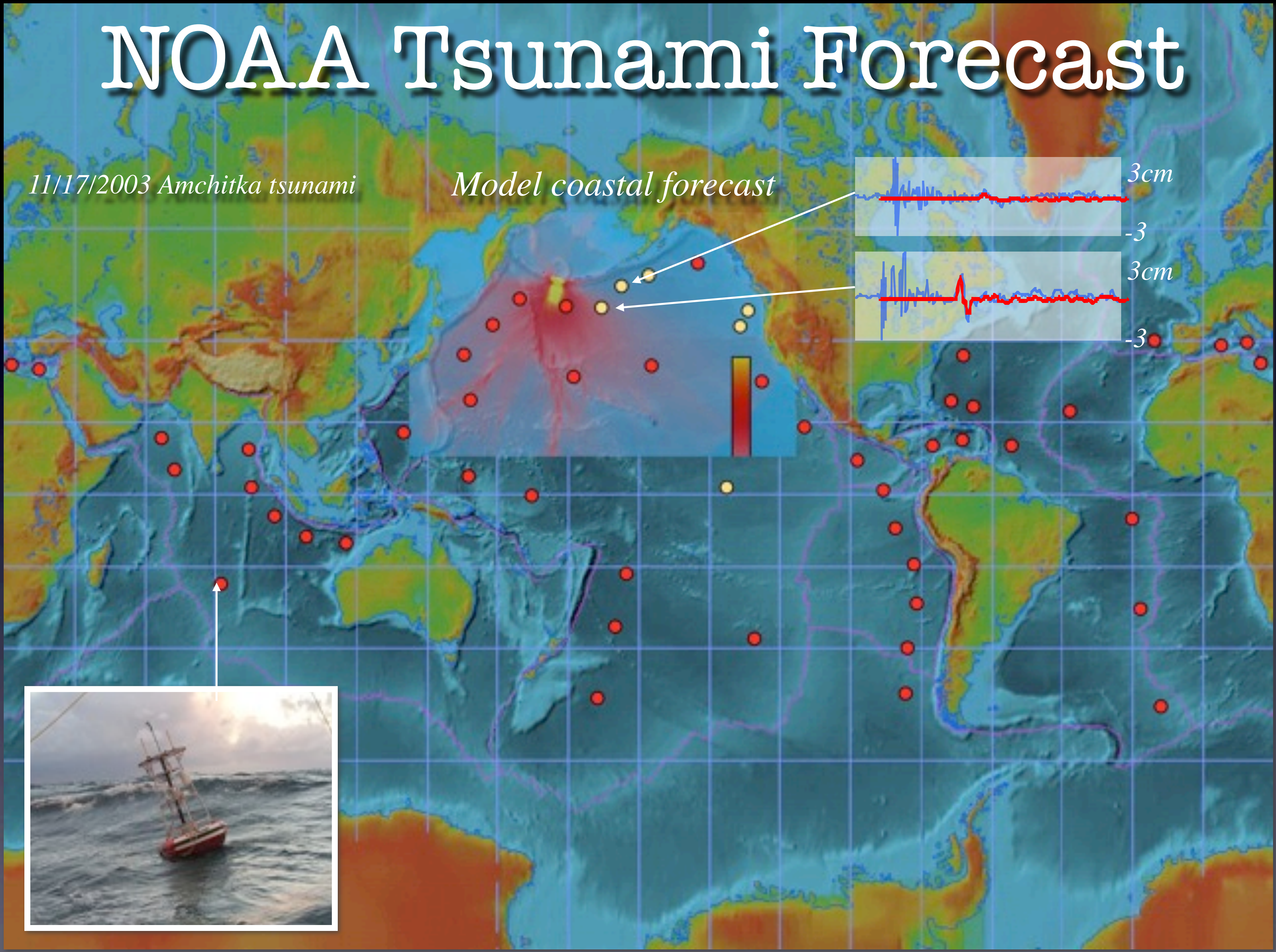

NOAA Tsunami Forecast
11/17/2003 Amchitka tsunami

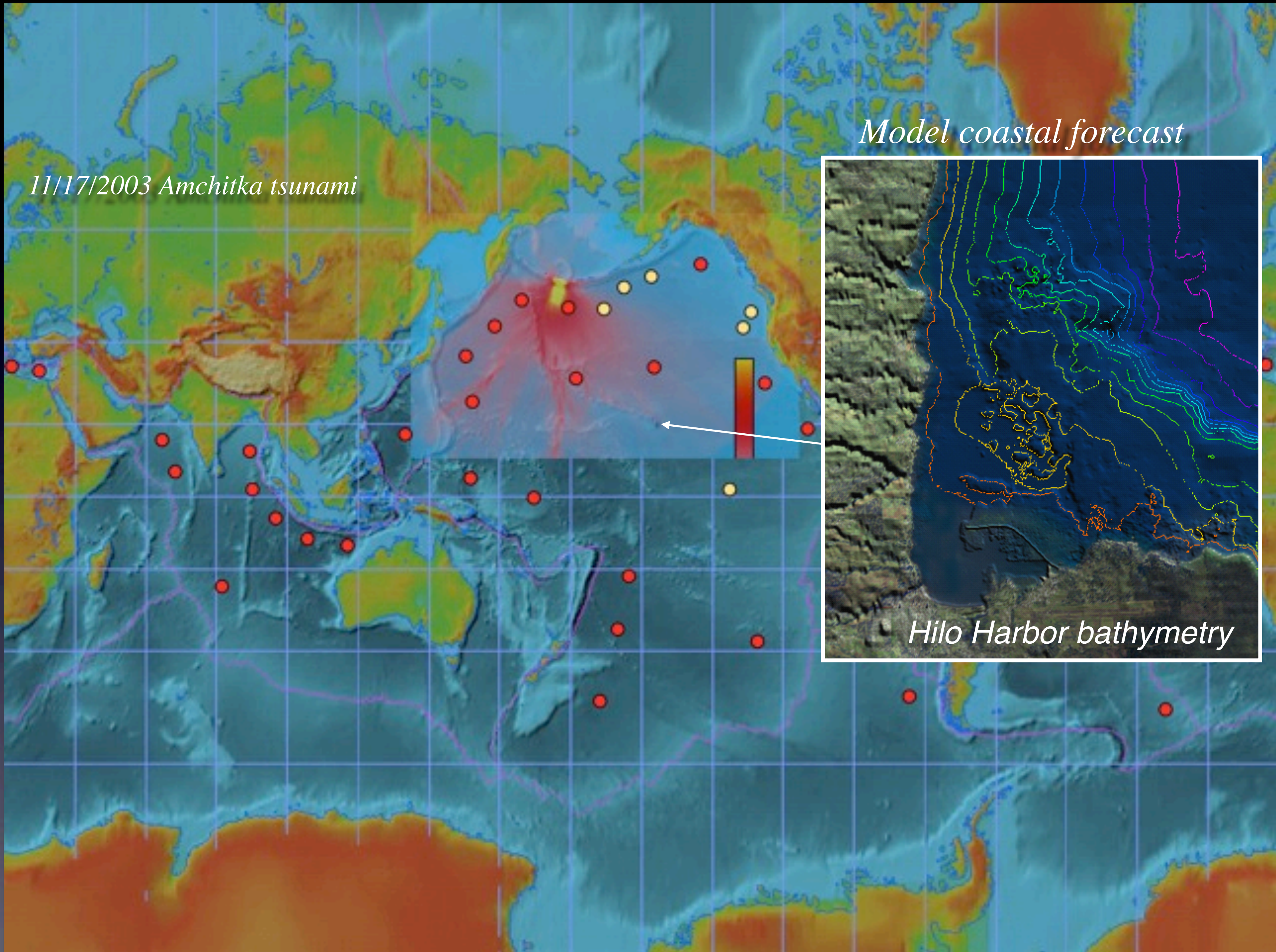
NOAA Tsunami Forecast



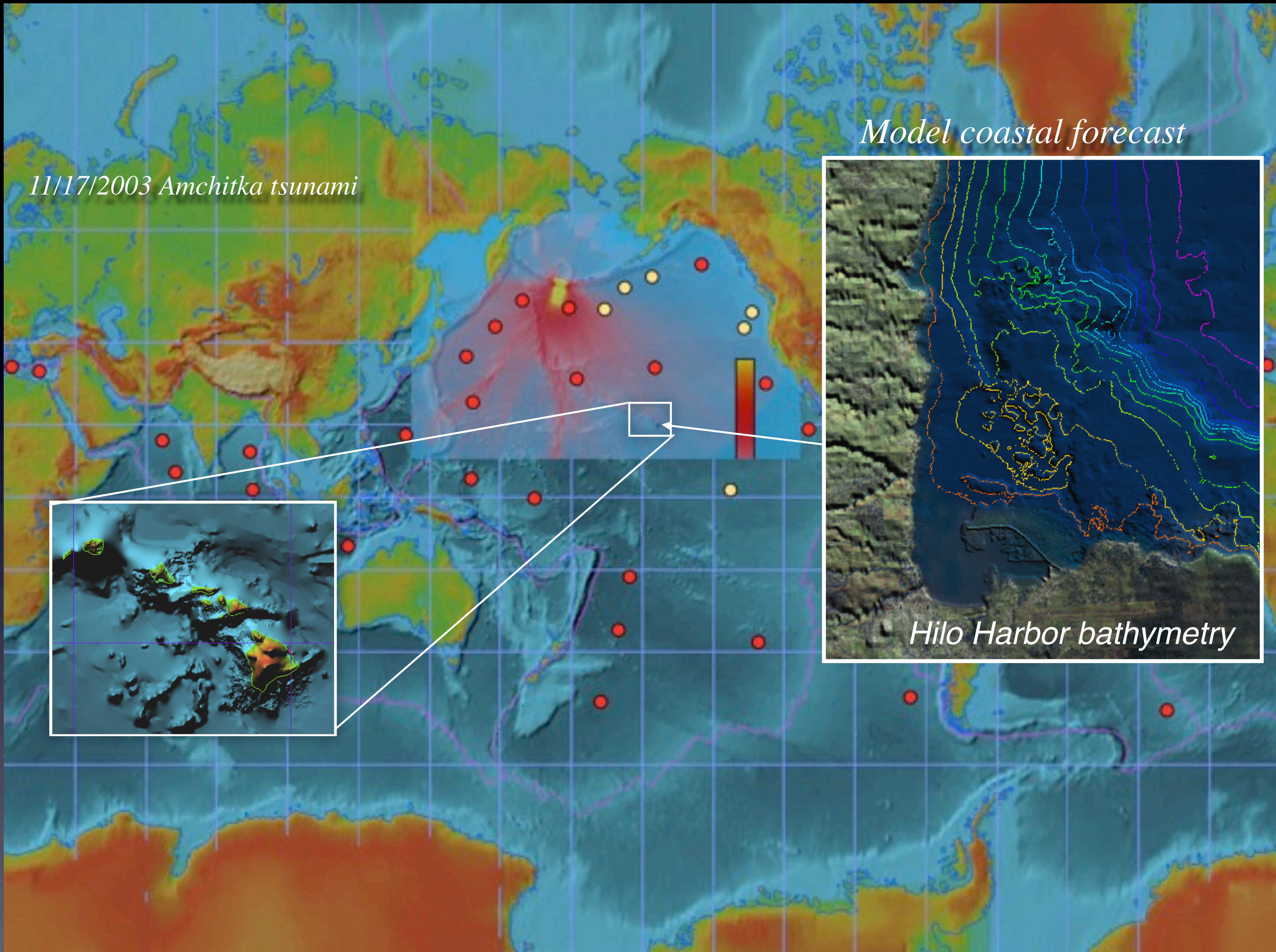
NOAA Tsunami Forecast



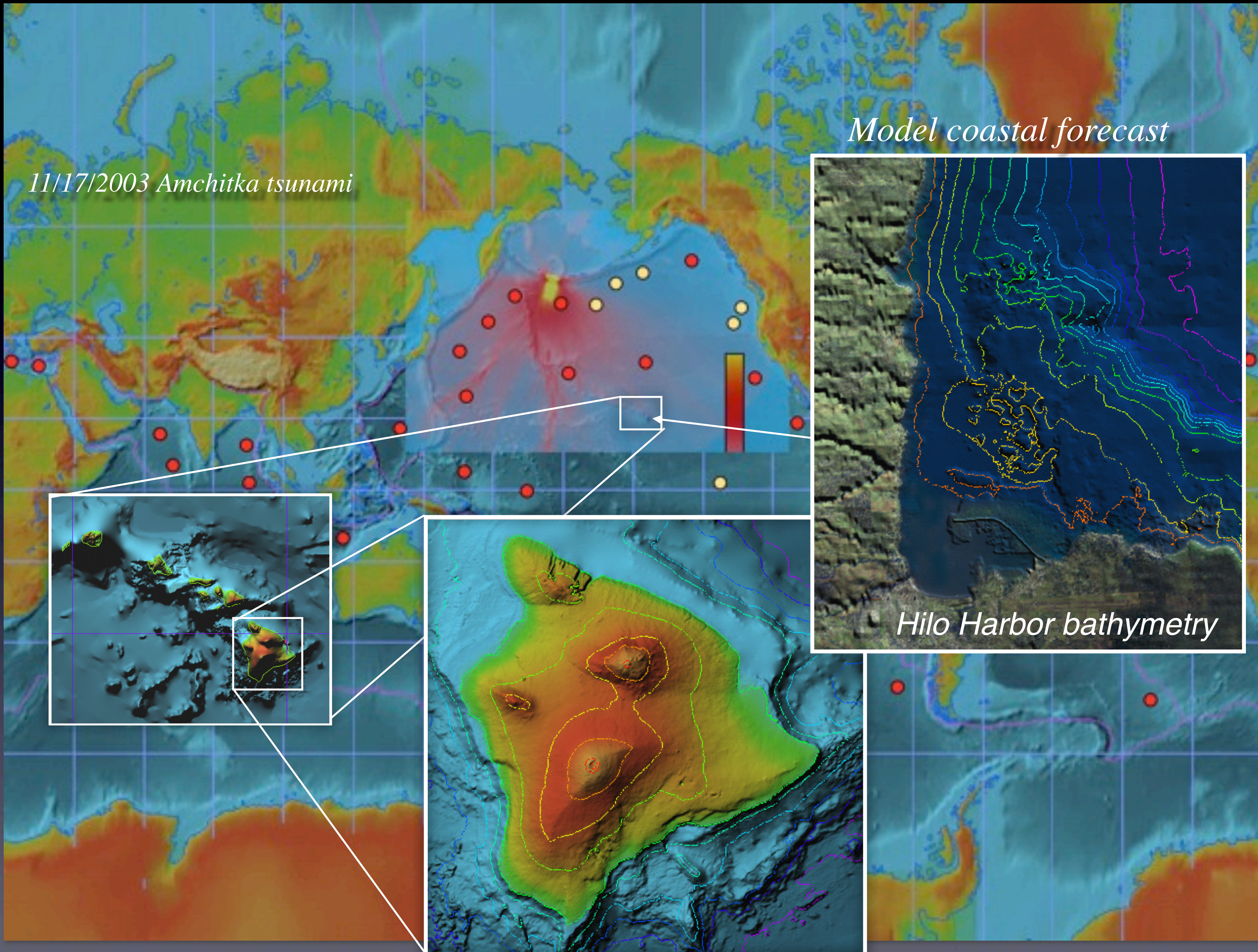

NOAA Tsunami Forecast
11/17/2003 Amchitka tsunami
Model coastal forecast
3cm
-3
3cm
-3

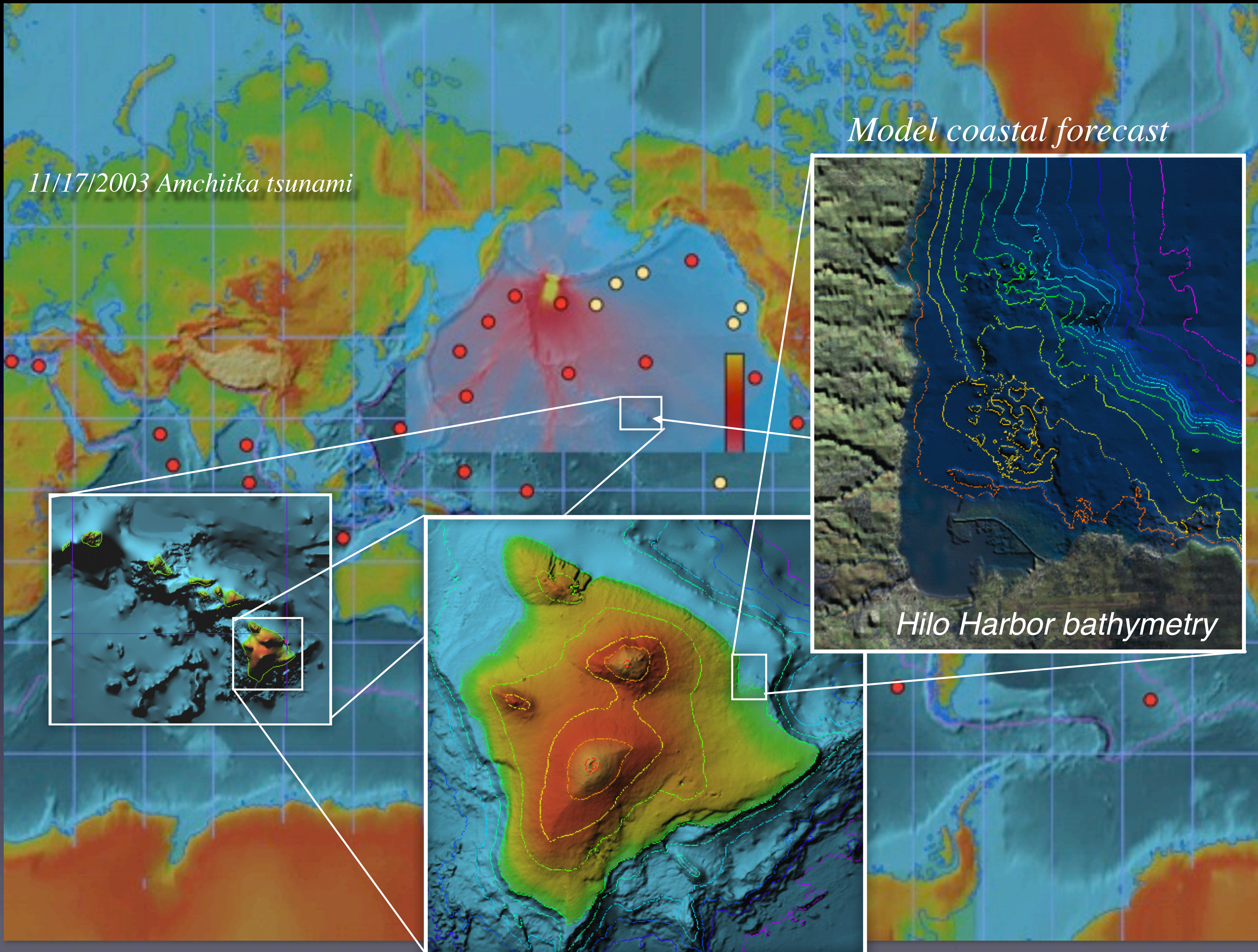


Wednesday, November 28, 2012

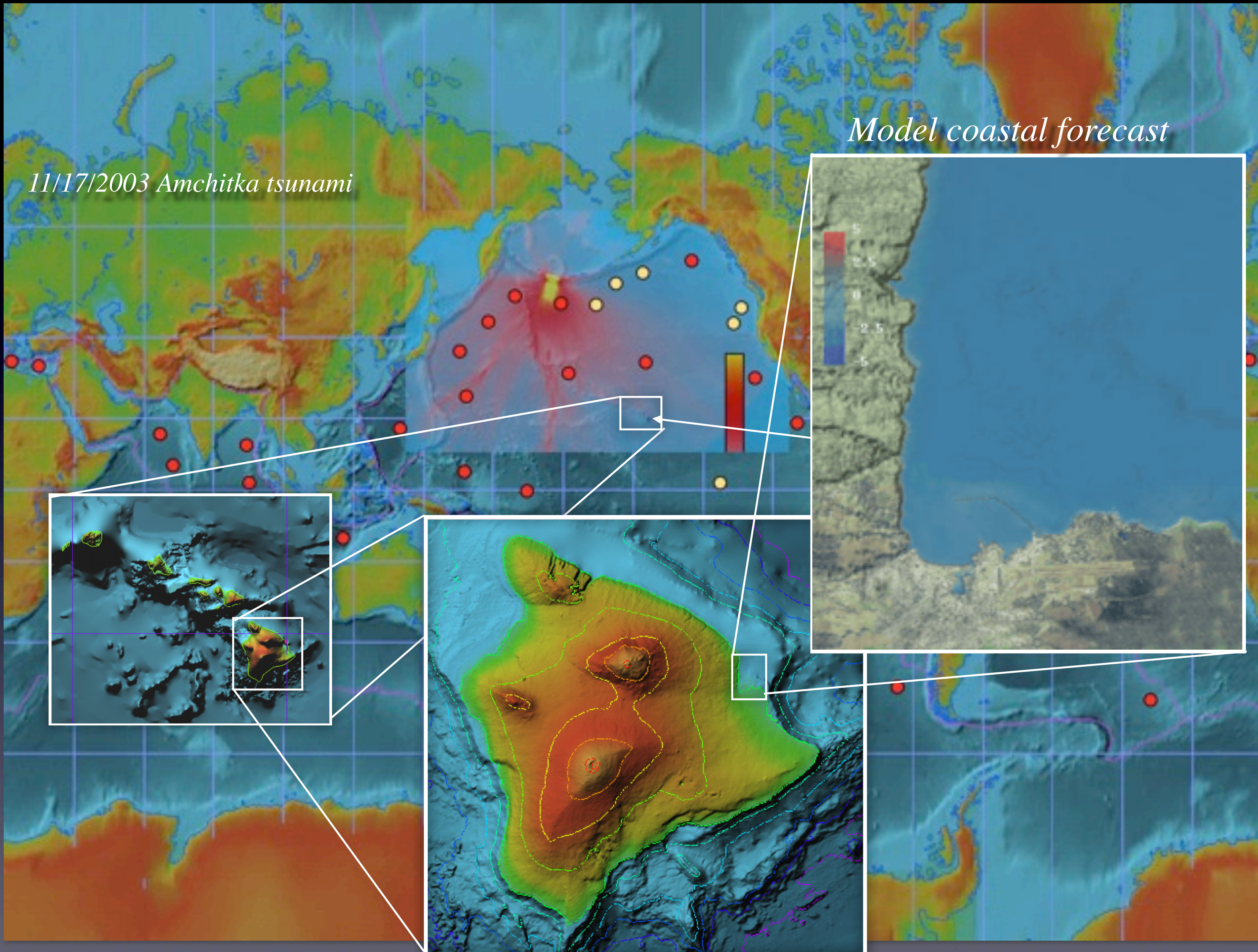


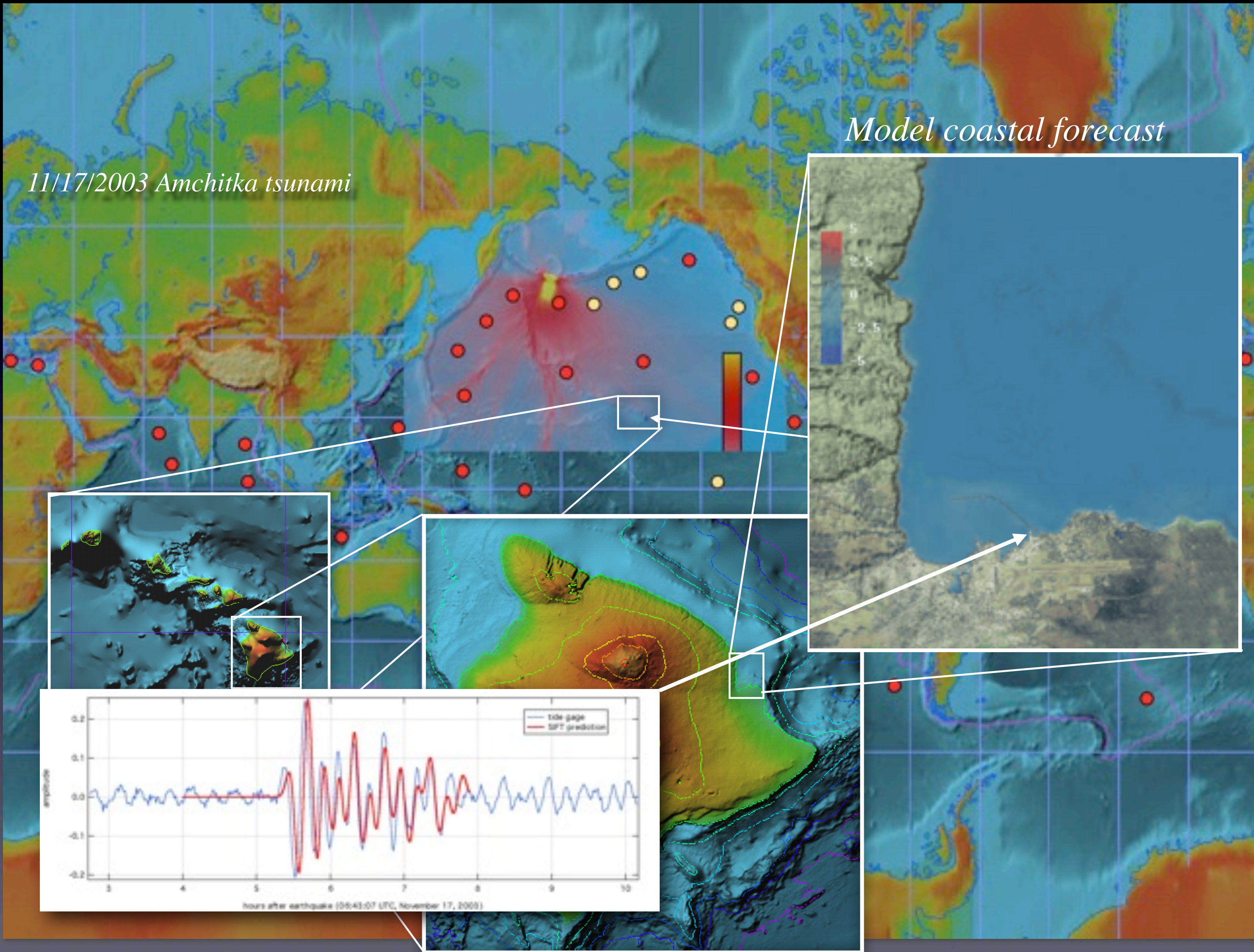
11/17/2003 Amchitka tsunami
Model coastal forecast
Hilo Harbor bathymetry


Model coastal forecast
11/17/2003 Amchitka tsunami
Hilo Harbor bathymetry

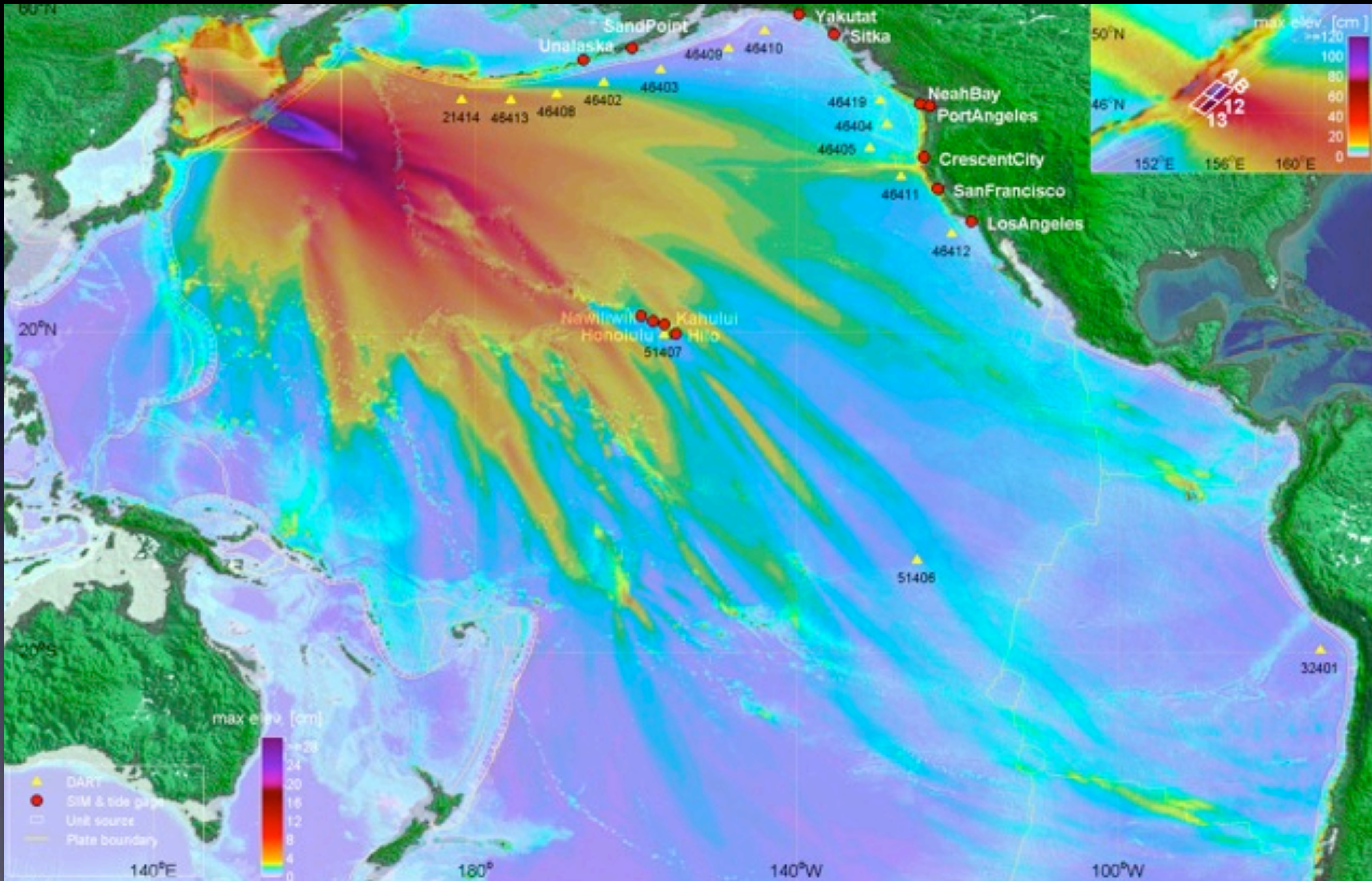


11/17/2003 Amchitka tsunami
Model coastal forecast
Hilo Harbor bathymetry

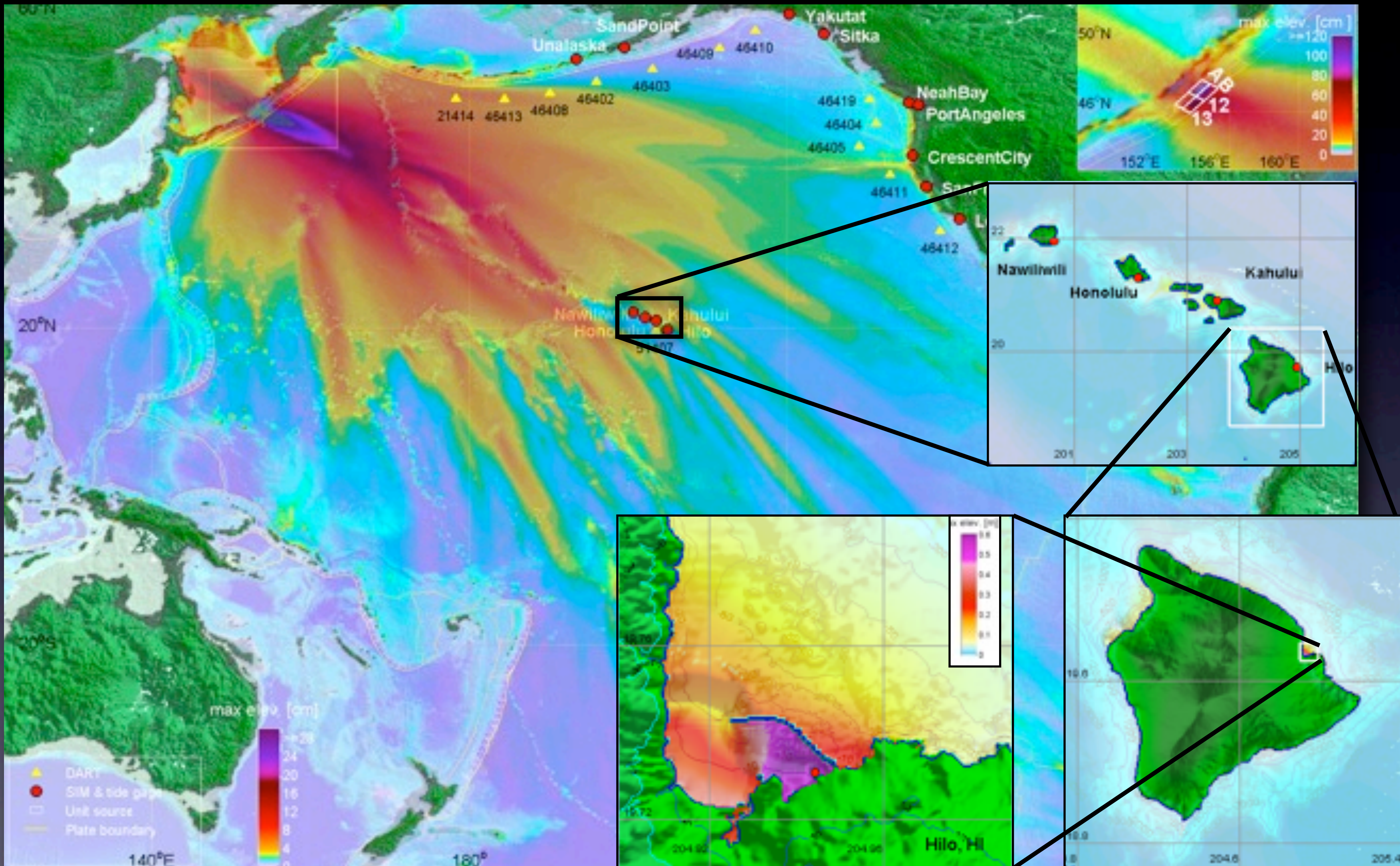

11/17/2003 Amchitka tsunami
Model coastal forecast


11/17/2003 Amchitka tsunami
Model coastal forecast
tide gage
SIFT prediction
amplitude

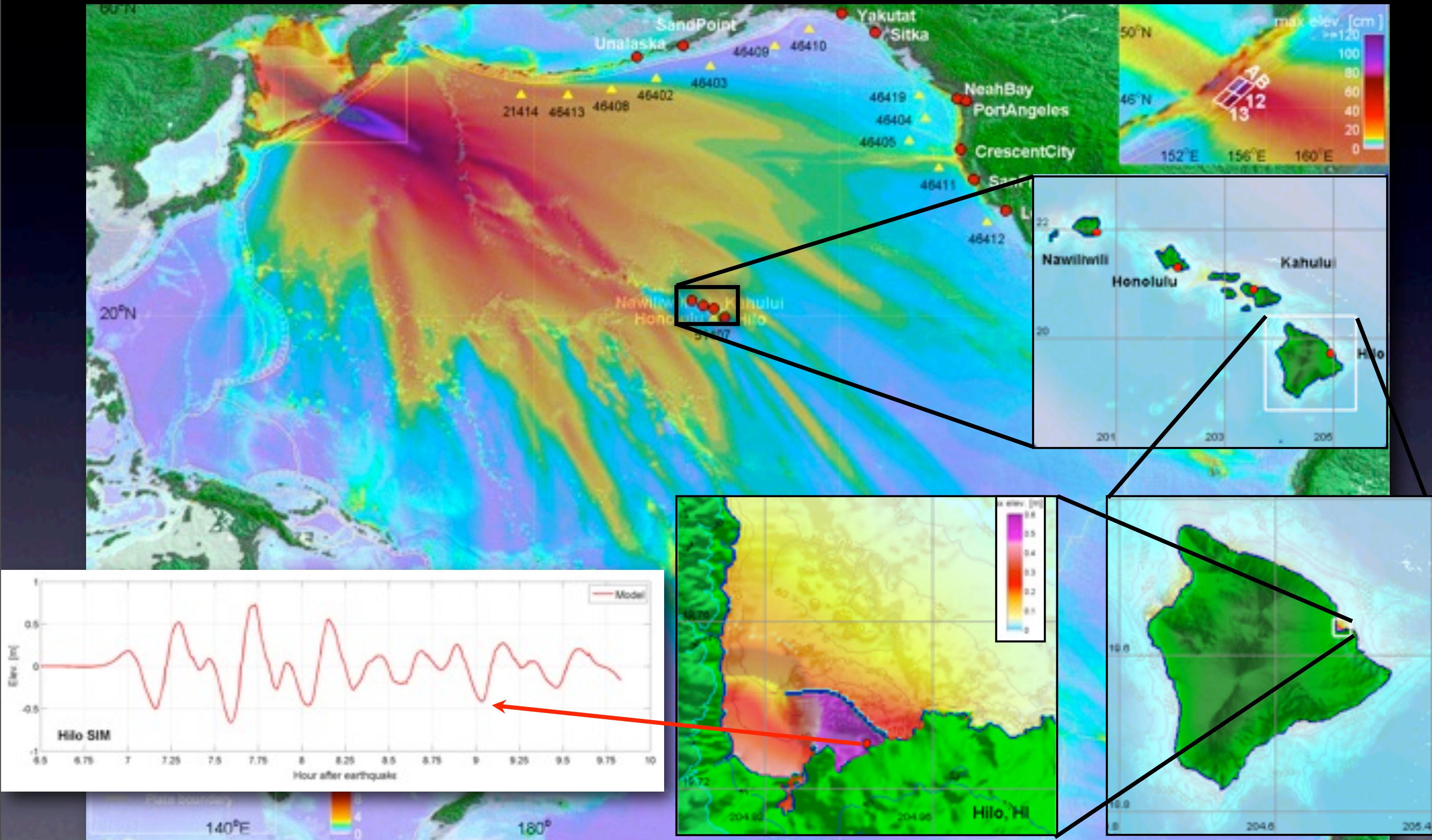
The November 15, 2006 Central Kuril Tsunami



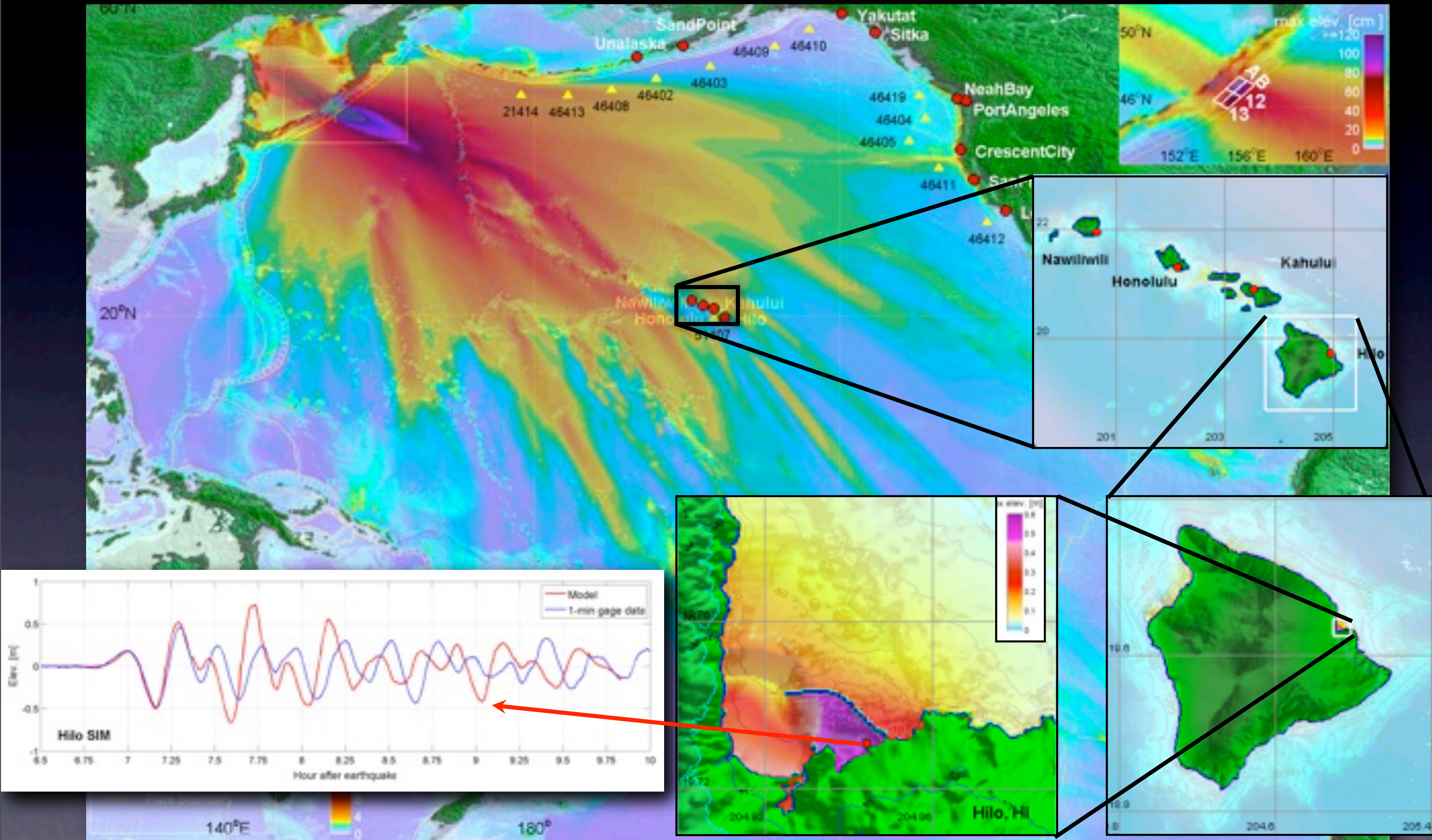
The November 15, 2006 Central Kuril Tsunami



The November 15, 2006 Central Kuril Tsunami

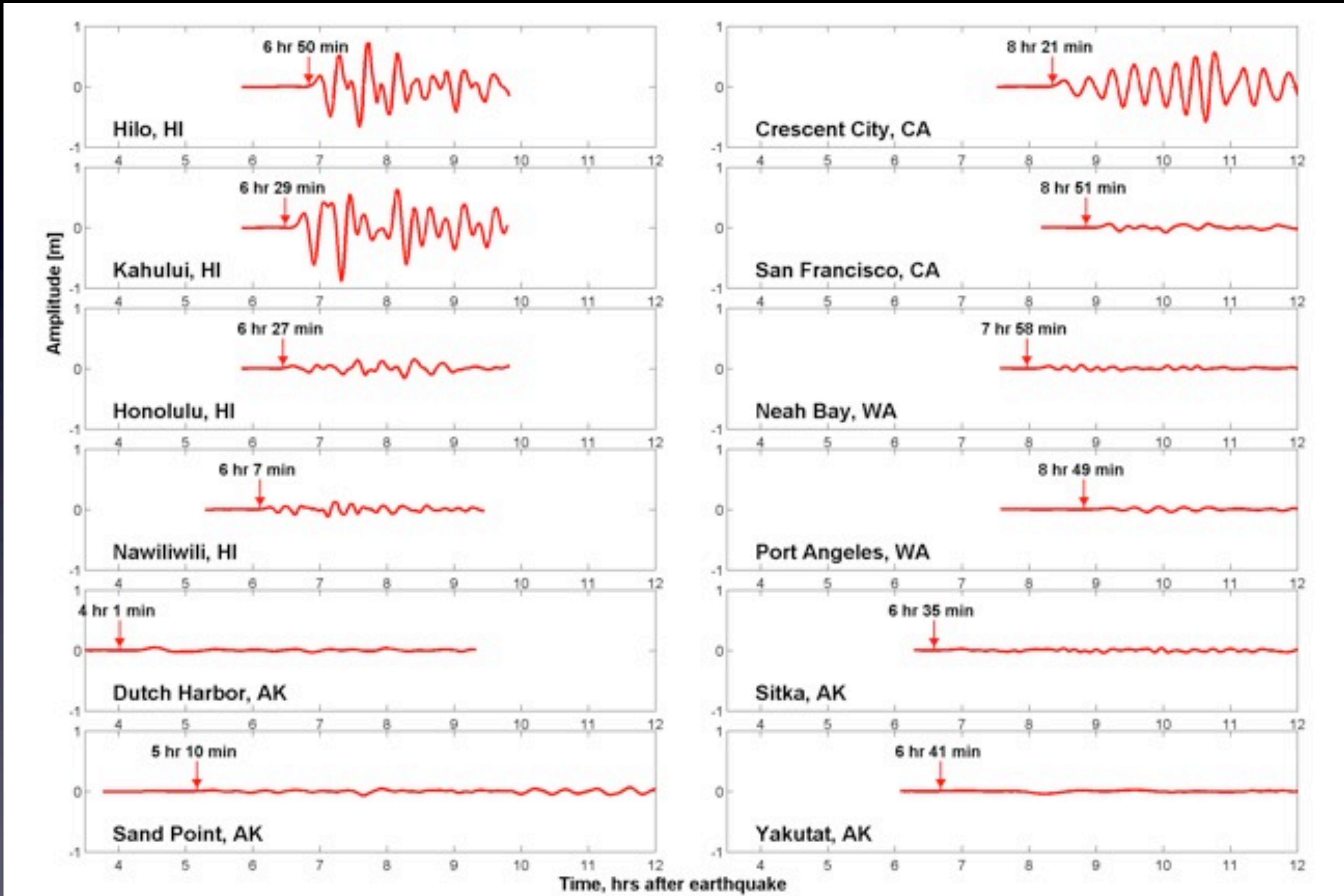


The November 15, 2006 Central Kuril Tsunami



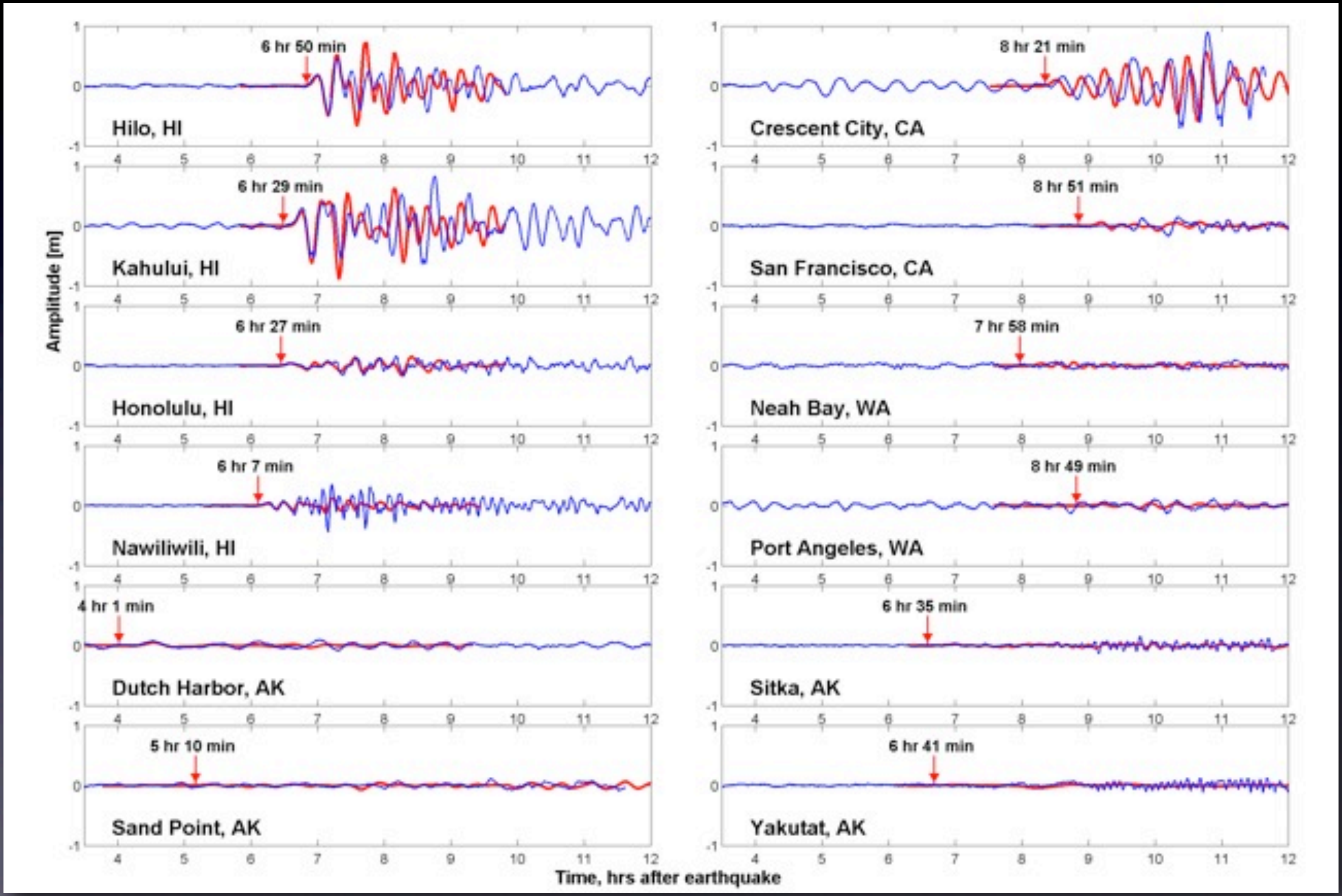
The November 15, 2006 Central Kuril Tsunami

Forecast vs **Observation**



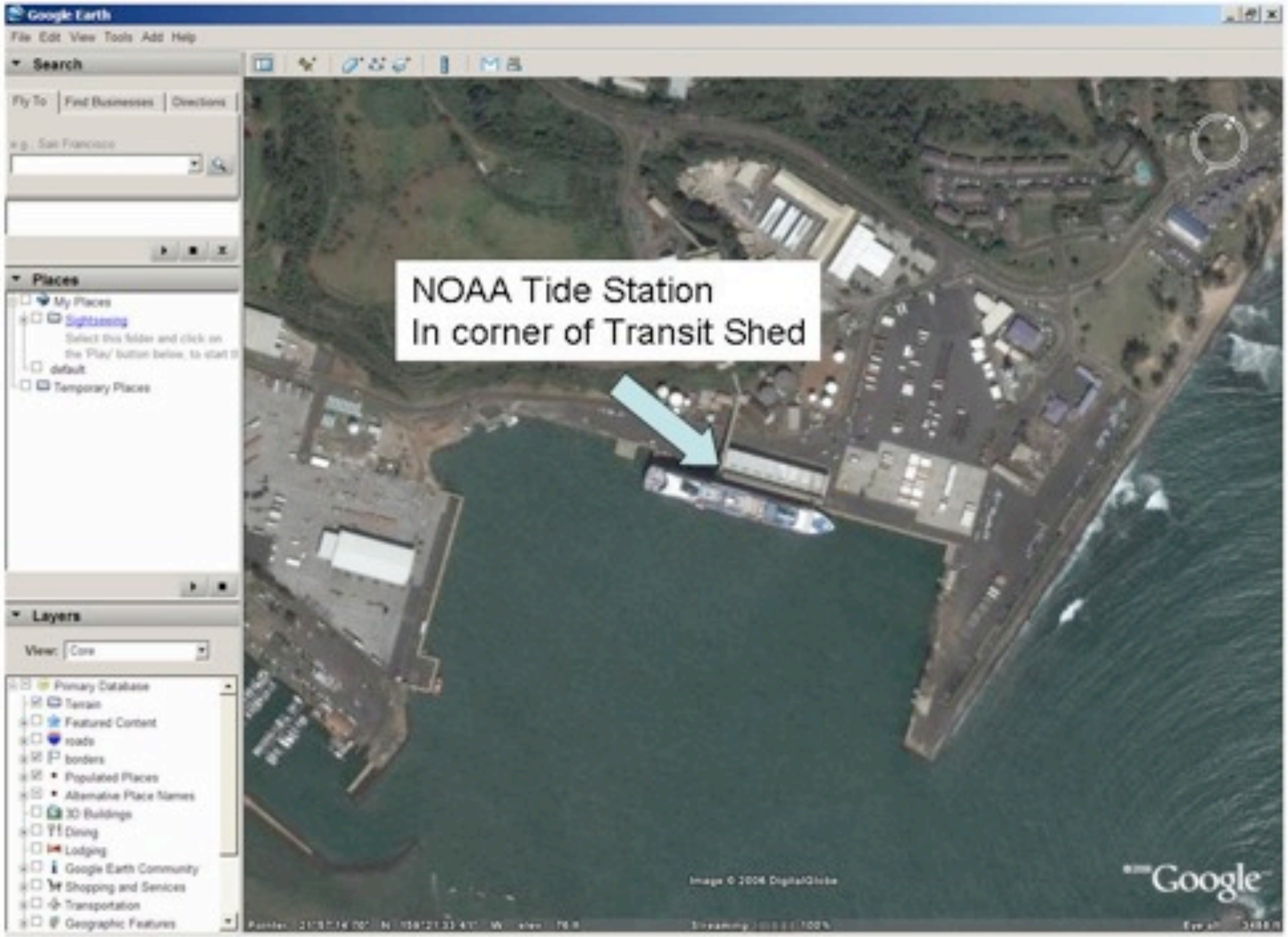
The November 15, 2006 Central Kuril Tsunami

Forecast vs **Observation**

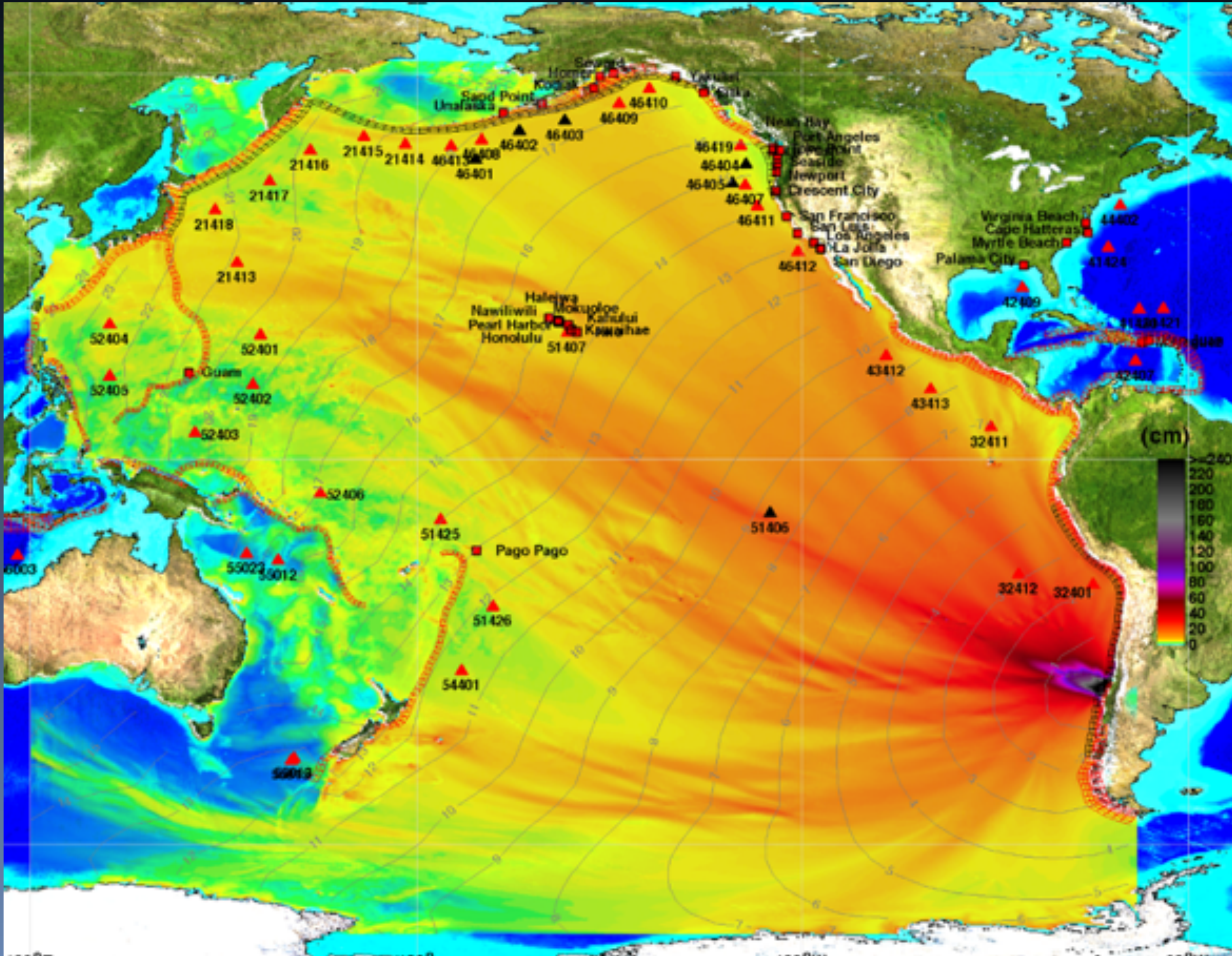


Nawiliwili Comparison

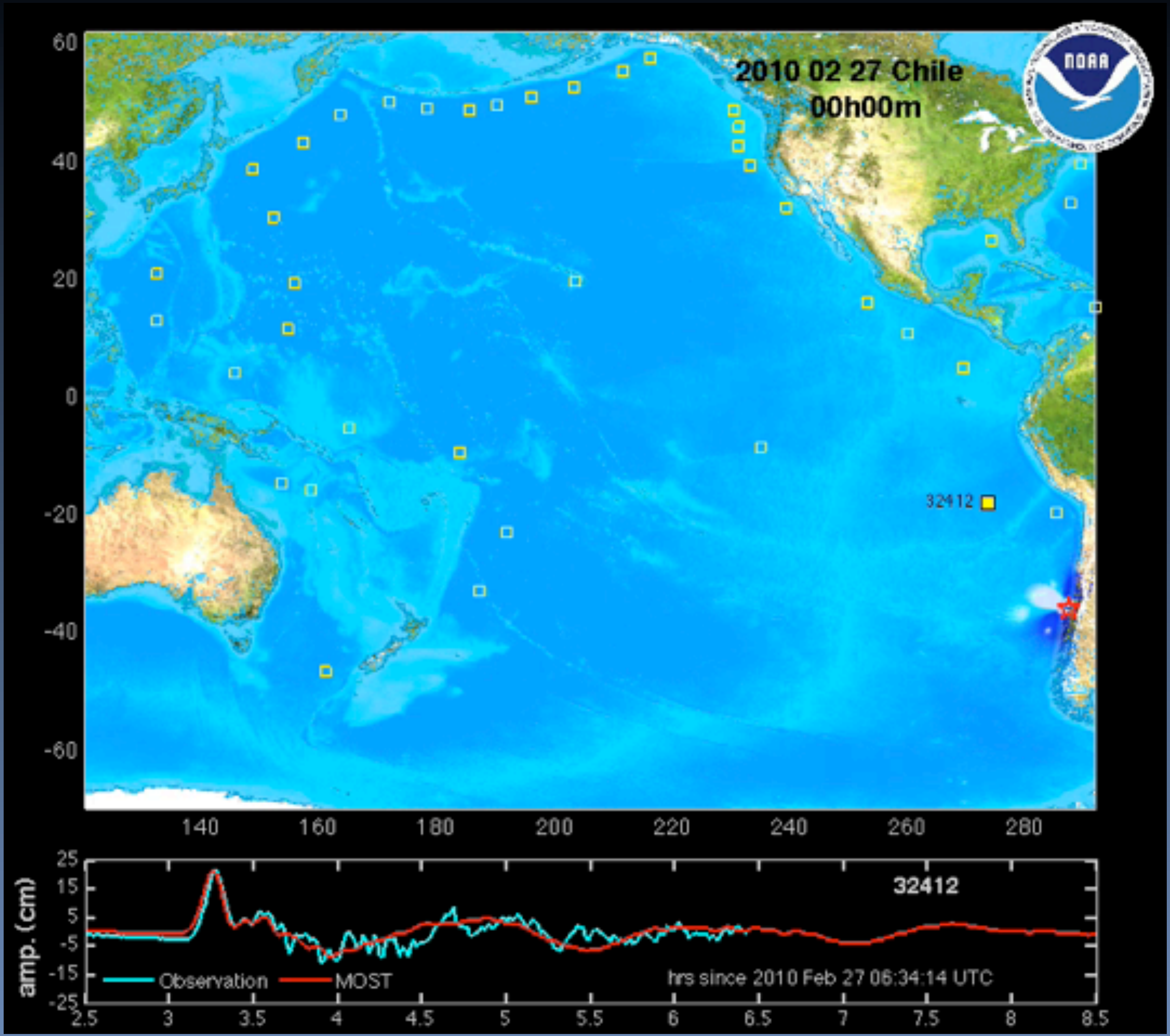
(Impacted by Cruise Ship?)



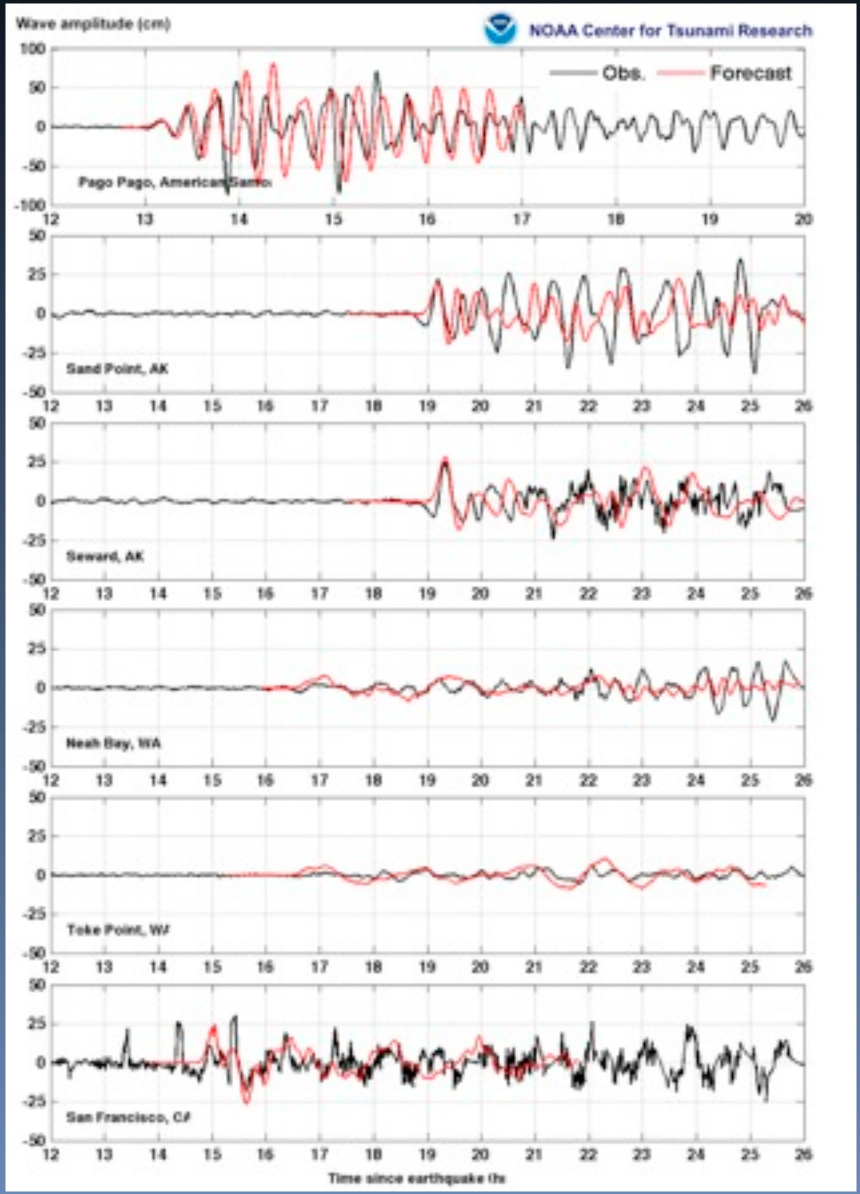
Tsunami Forecast Overview, Chile 2010



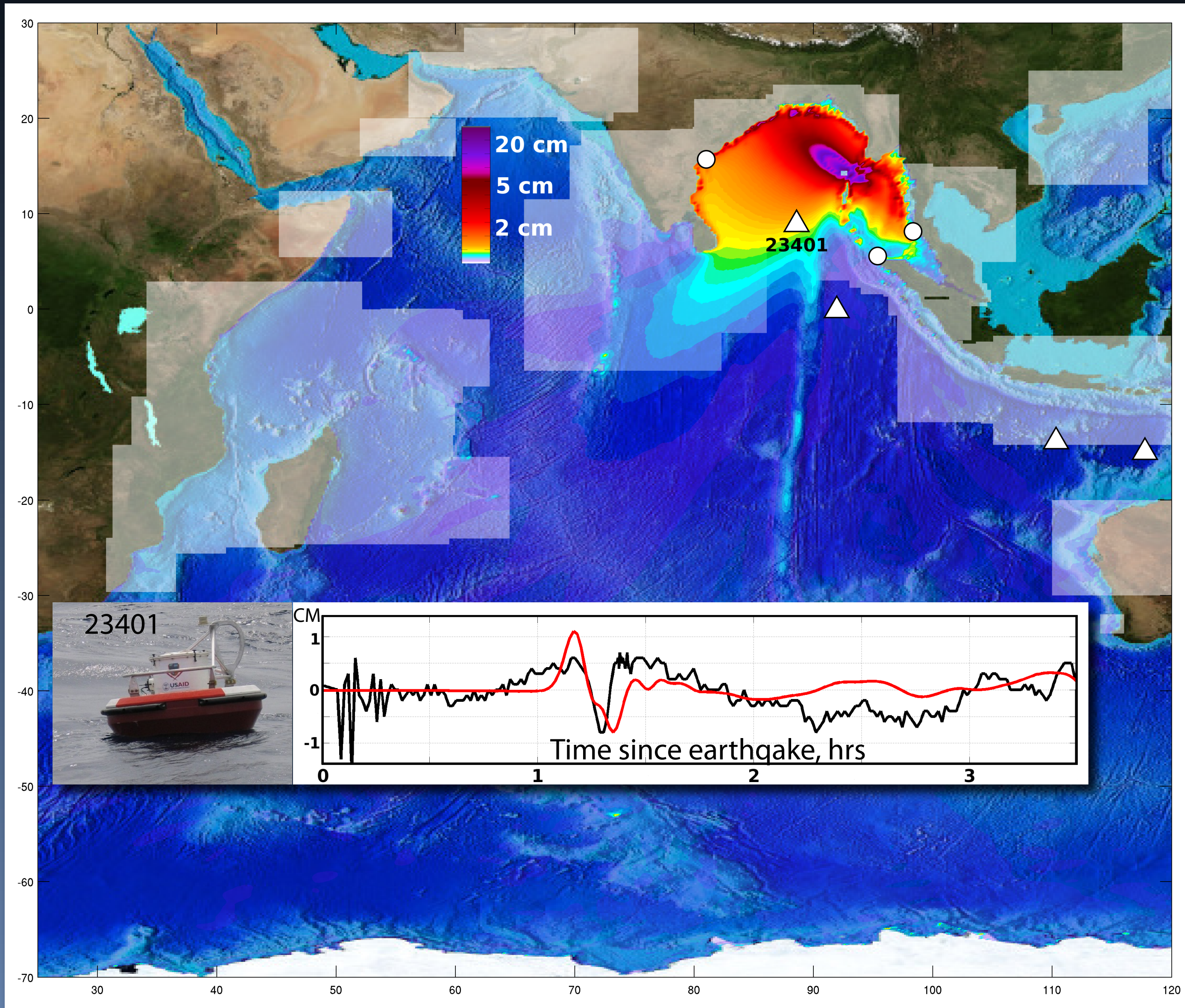
Tsunami Forecast Overview, Chile 2010

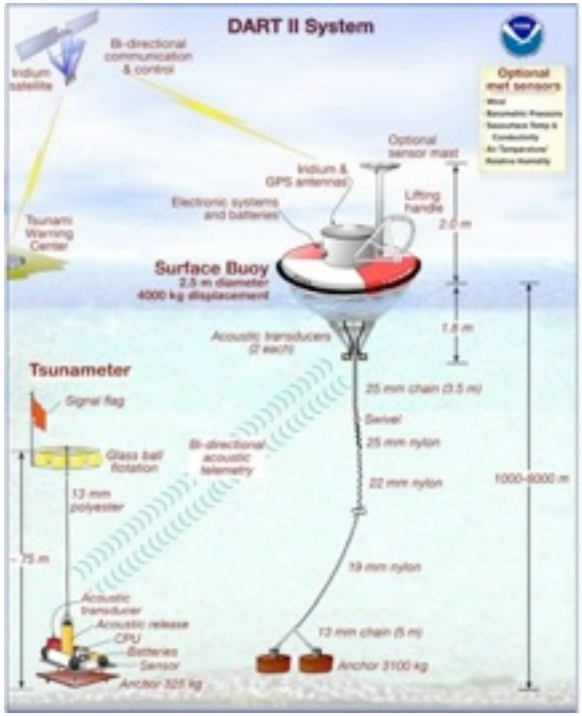


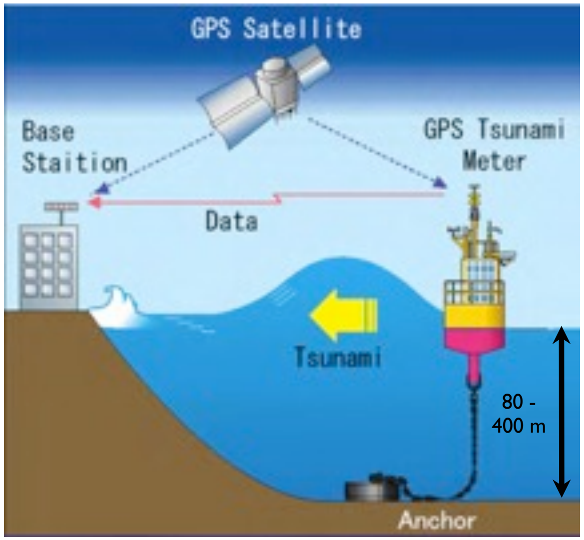
Results: Tide gauge comparisons, Chile 2010



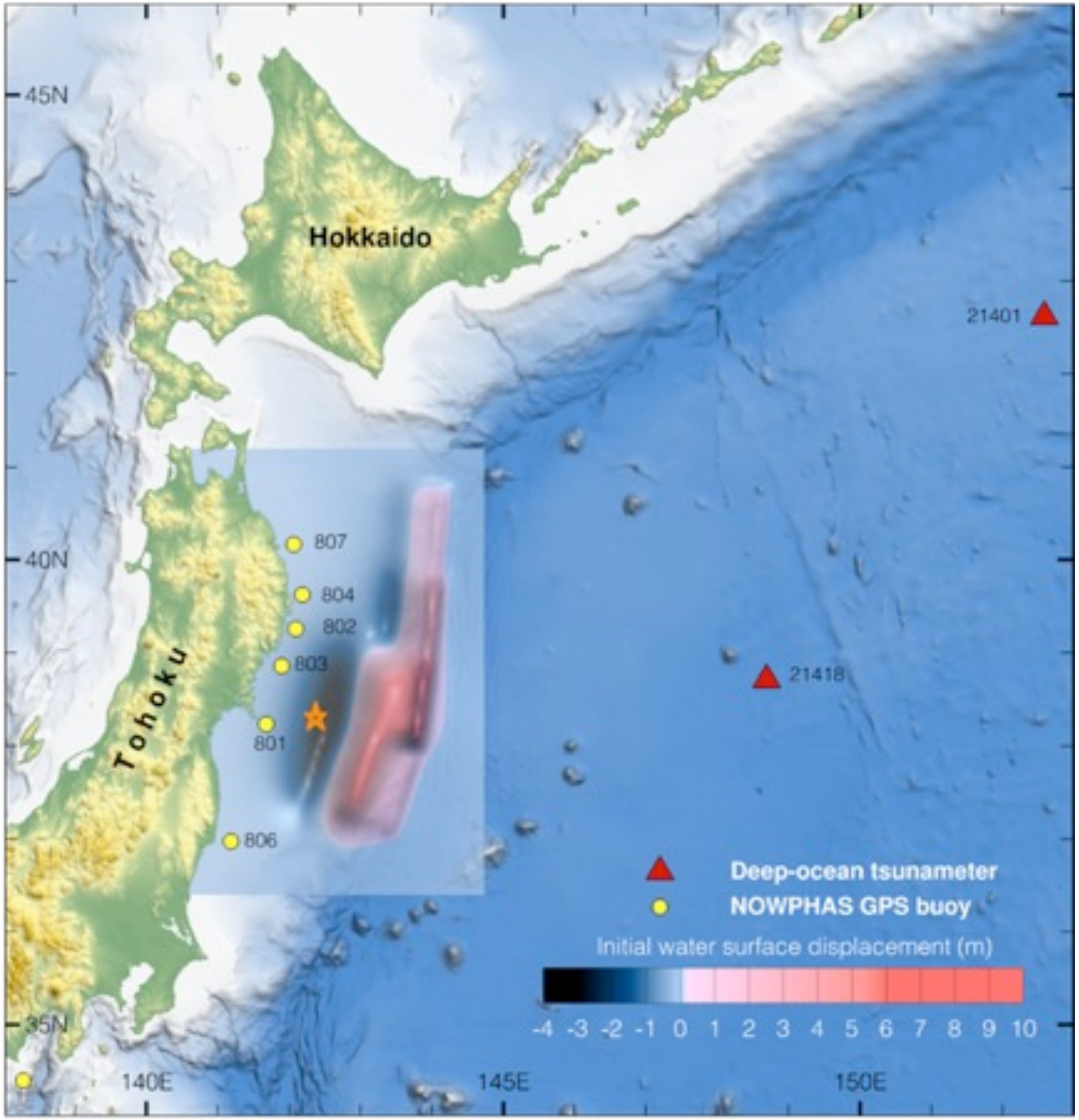
August 10, 2009 Andaman

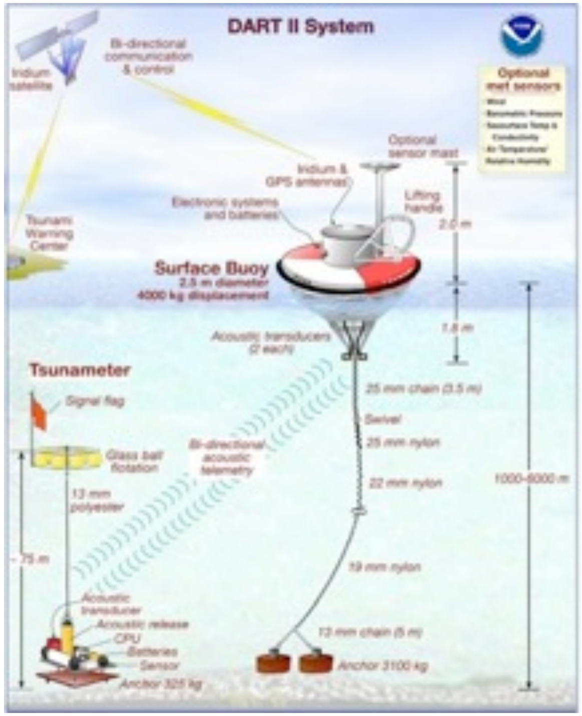


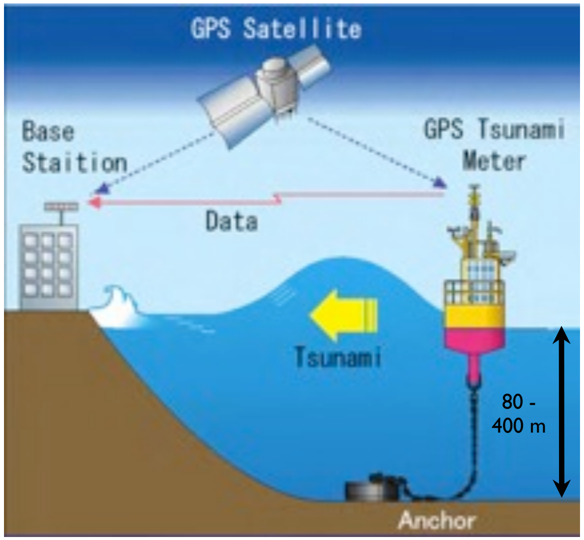




Courtesy of Kato et al.







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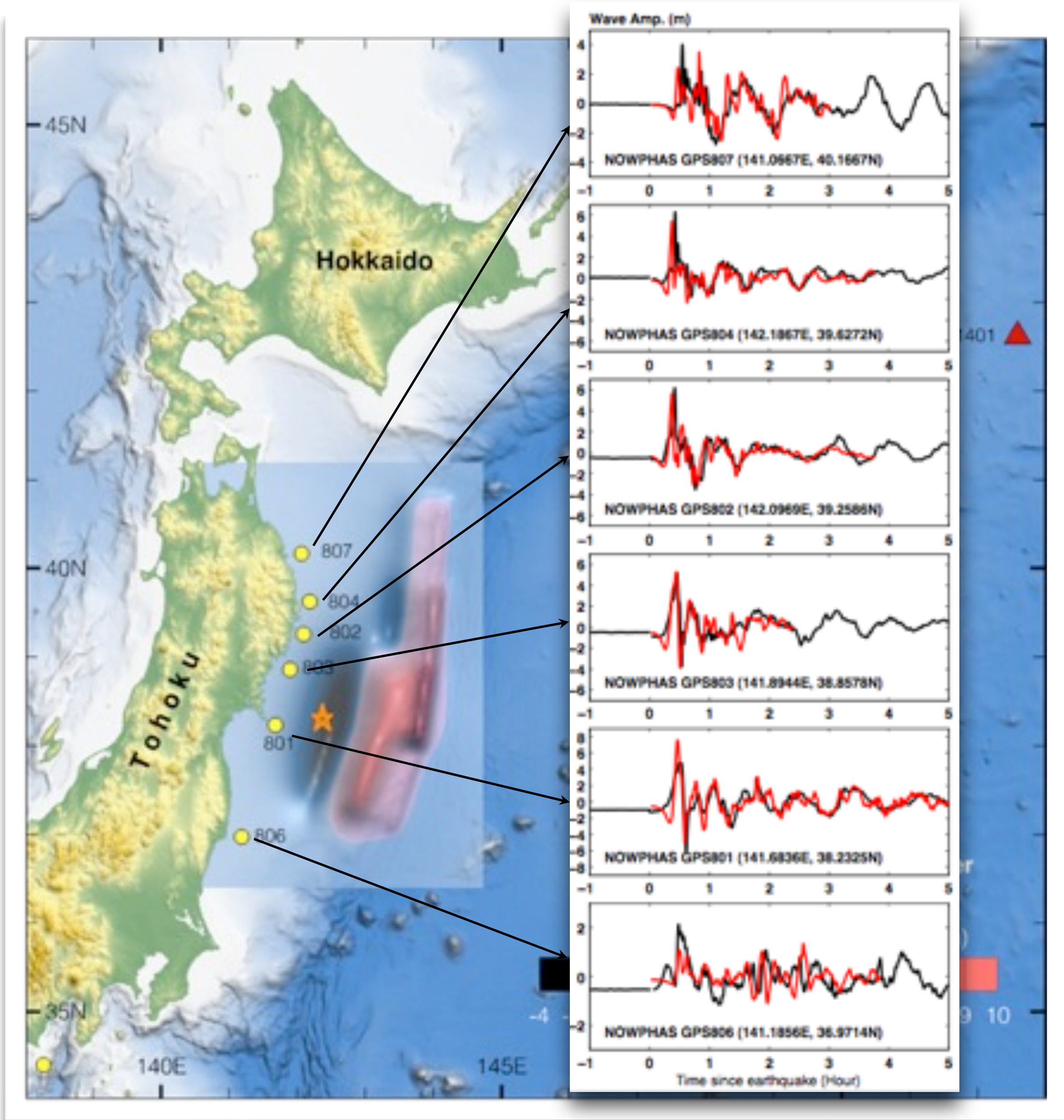
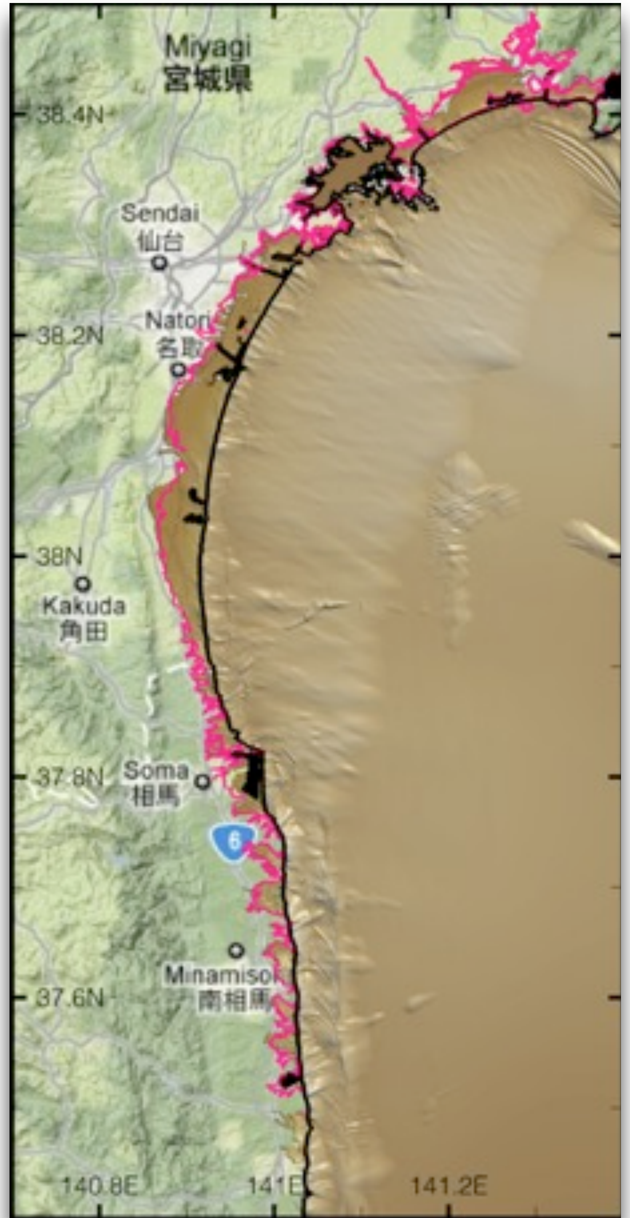
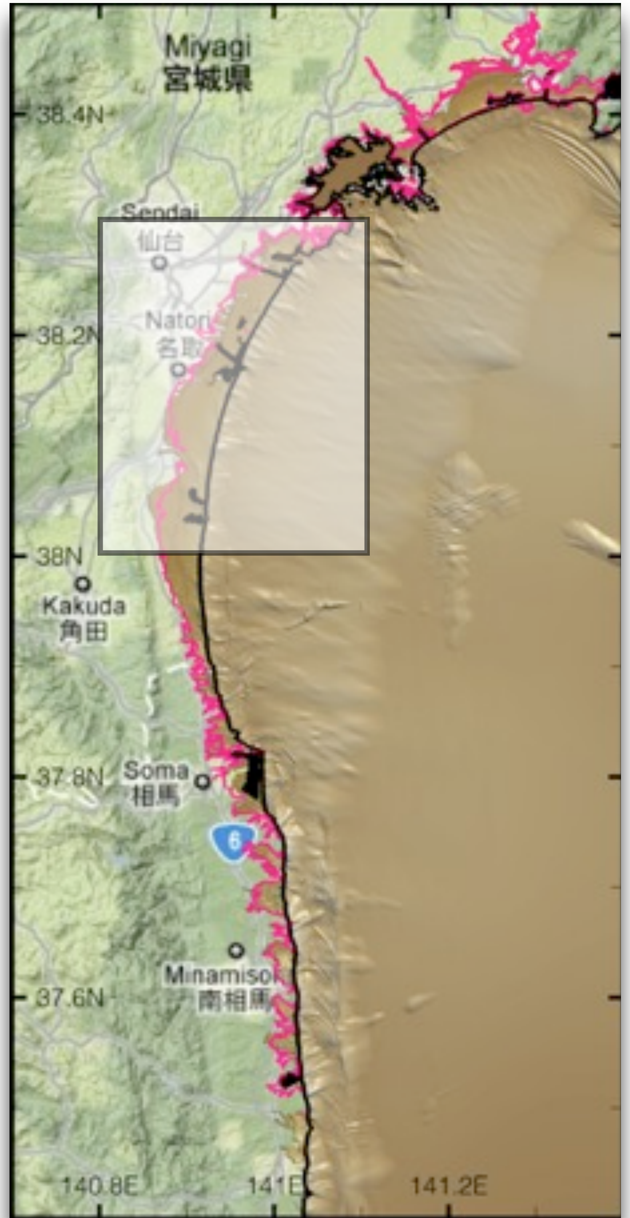


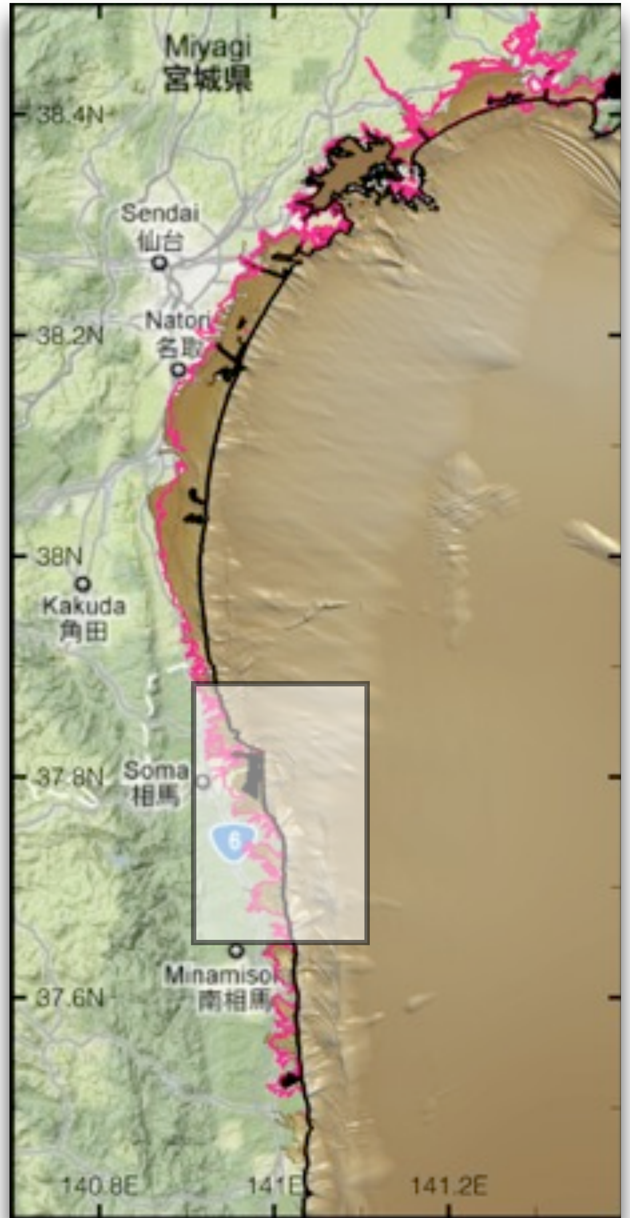
Local Forecast Test



Local Forecast Test

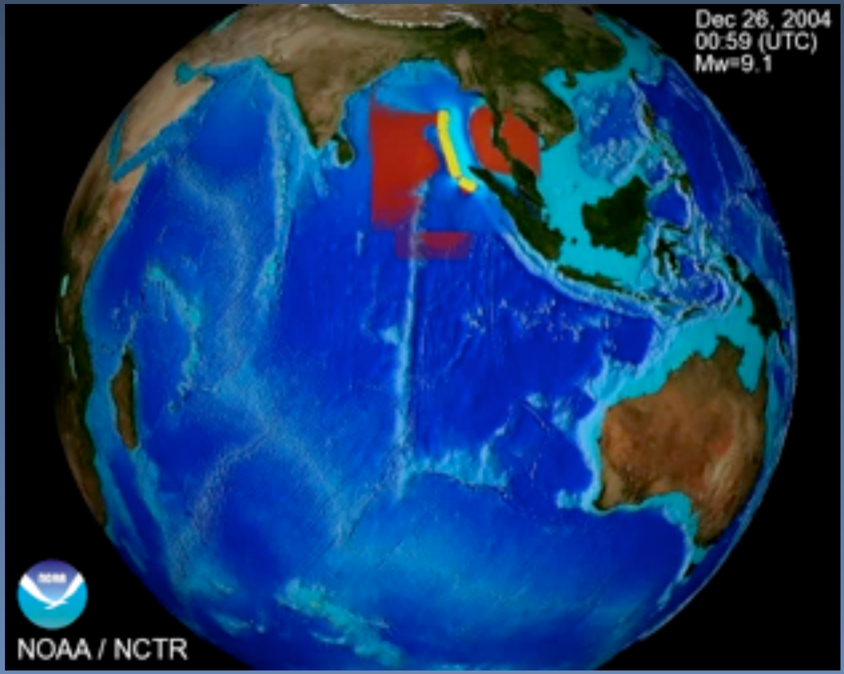


Local Forecast Test



Summary - NOAA's numerical forecasting techniques

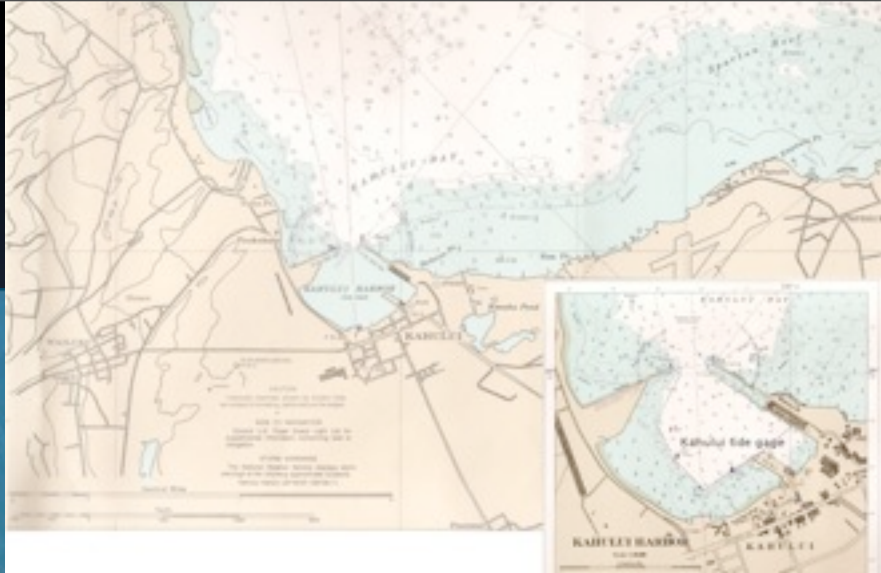
- Earthquakes are the major generation mechanism, but tsunamis can have more than one.
- The source is complicated, so we measure the wave directly.
- DART buoy data helps us to constrain the model
- Inverted propagation model is used to force the inundation model.

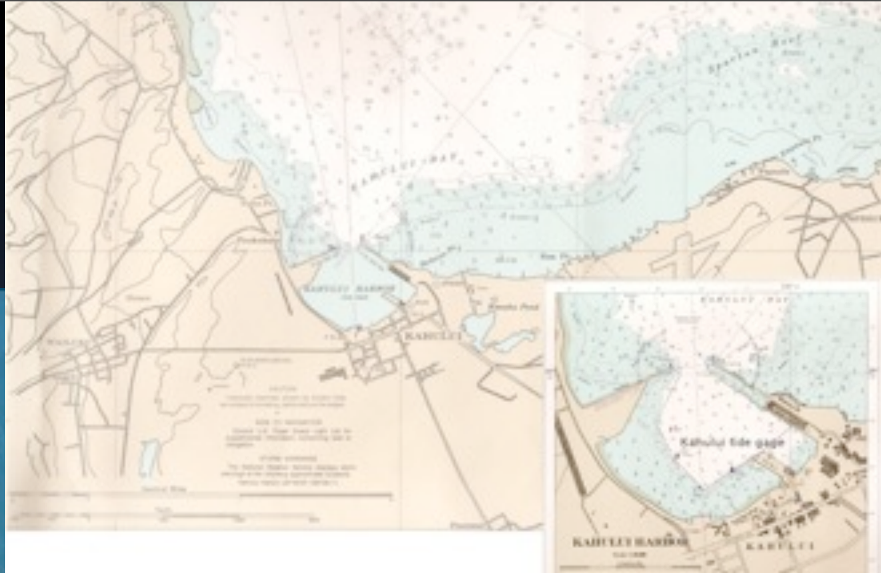


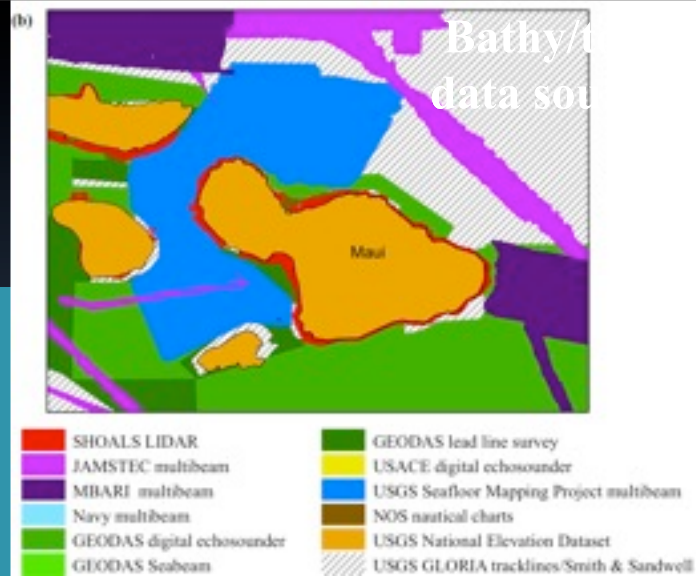
Stop Here

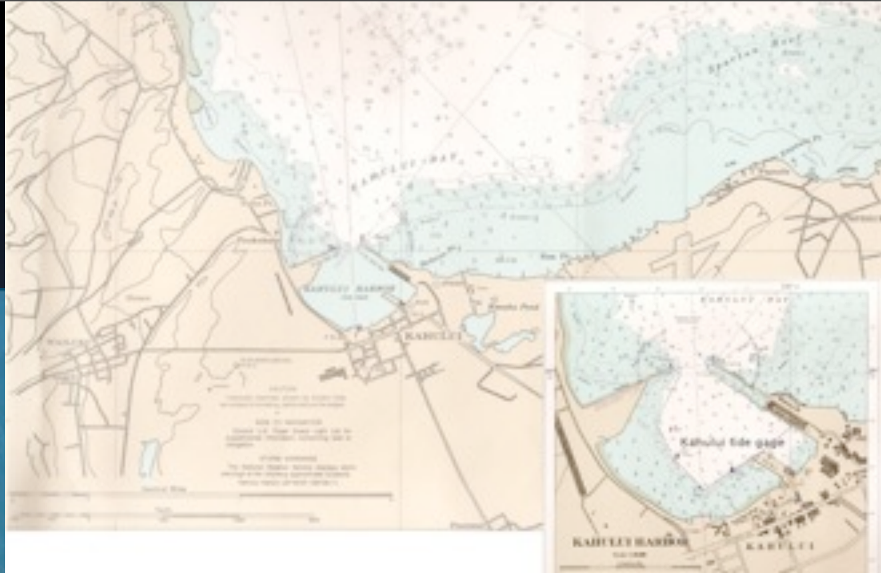
Developing Inundation Grids

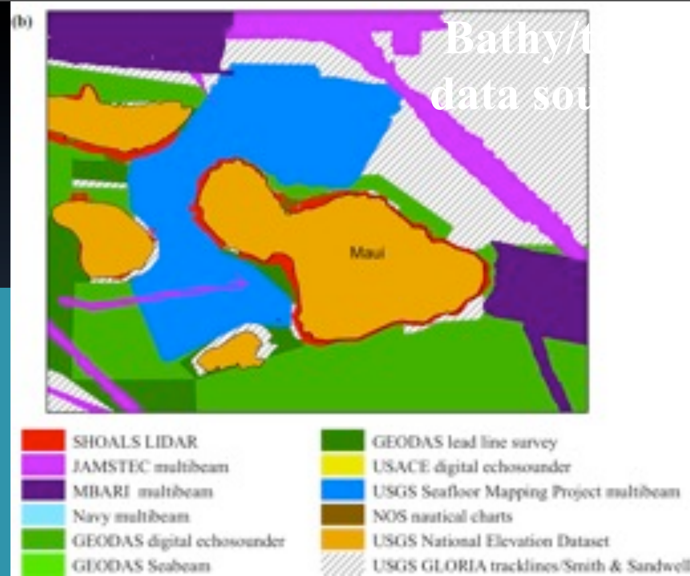
- Reference model uses the highest quality and resolution available for a community
- Model from different sources is combined to form 3 nested grids
- Tested against historical data, and for robustness
- Highly optimized grids are derived from the reference grids


Kahului tide gage


KAHULUI HARBOR
KAHULUI
Kahului tide gage


(b)
Maui
SHOALS LIDAR
JAMSTEC multibeam
MBARI multibeam
Navy multibeam
GEODAS digital echosounder
GEODAS Seabeam
GEODAS lead line survey
USACE digital echosounder
USGS Seafloor Mapping Project multibeam
NOS nautical charts
USGS National Elevation Dataset
USGS GLORIA tracklines/Smith & Sandwell


KAHULUI HARBOR
KAHULUI
Kahului tide gage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Maui
SHOALS LIDAR
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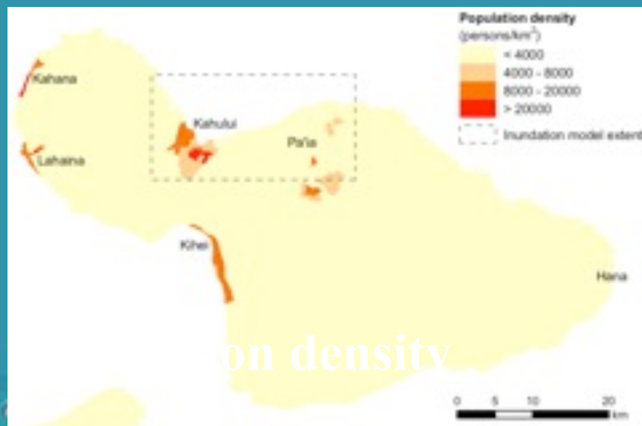
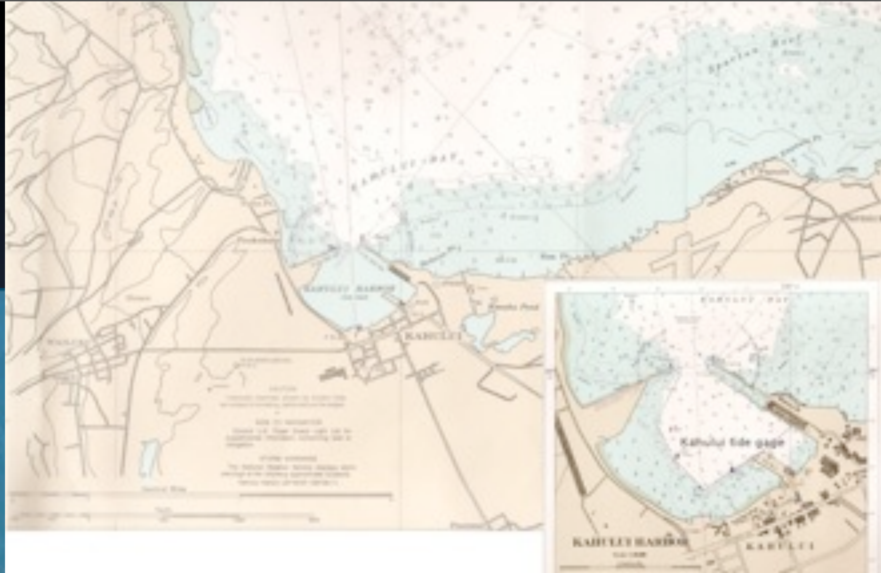
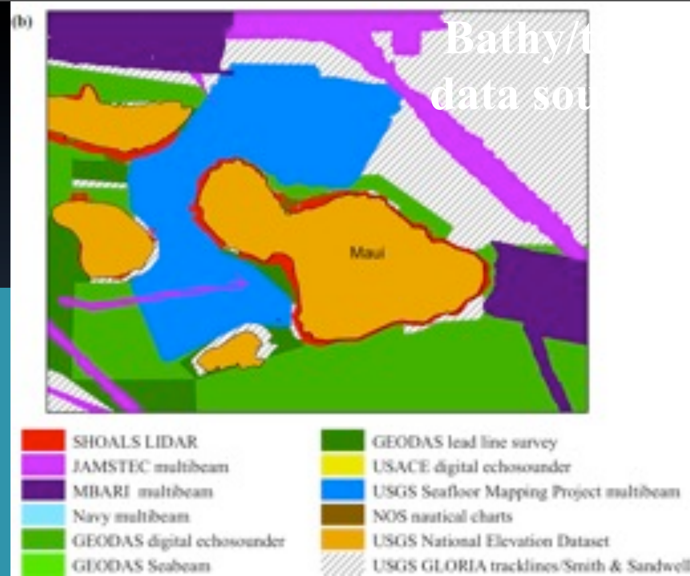

Population density
(persons/km^2)
< 4000
4000 - 8000
8000 - 20000
> 20000
Inundation model extent
Kahana
Lahaina
Kahului
Pa'ia
Kihei
Hana
0 5 10 20
km


KAHULUI HARBOR
KAHULUI
Kahului tide gage


(b)
Bathy/t
data sou
Maui
SHOALS LIDAR
JAMSTEC multibeam
MBARI multibeam
Navy multibeam
GEODAS digital echosounder
GEODAS Seabeam
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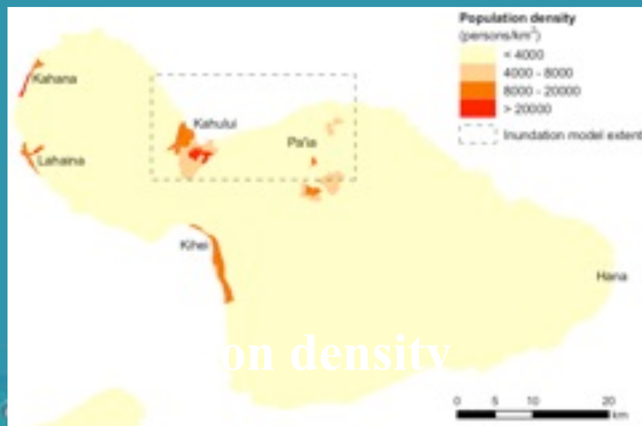
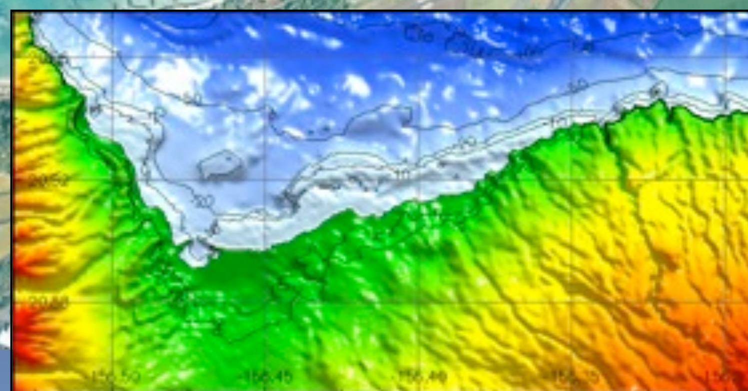
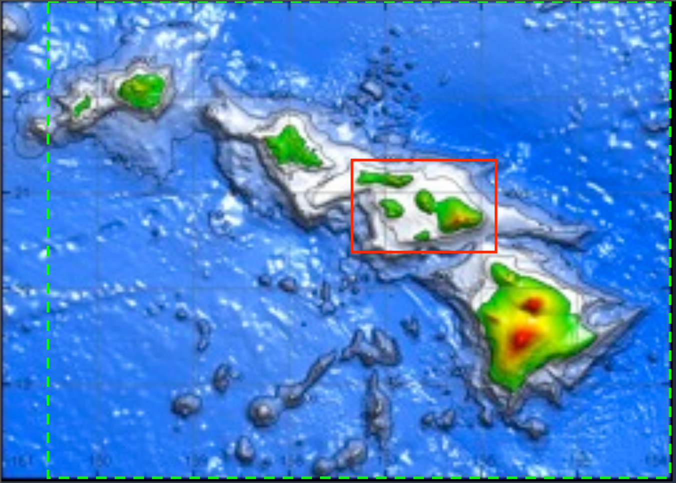
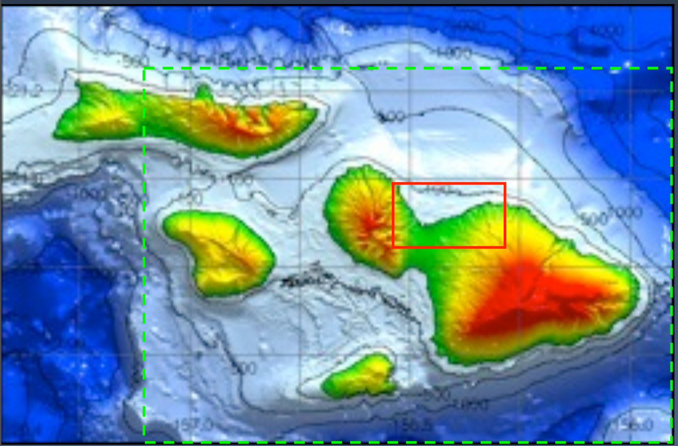
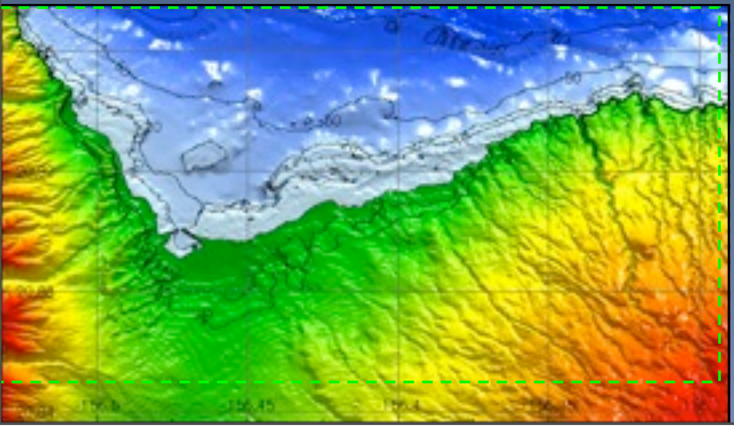
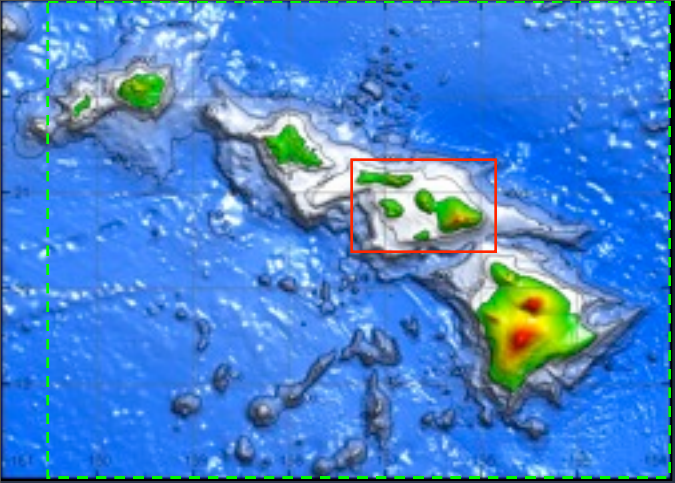

Population density
(persons/km²)
< 4000
4000 - 8000
8000 - 20000
> 20000
Inundation model extent
Kahana
Lahaina
Kahului
Pa'ia
Kihei
Hana
on density
0
5
10
20
km

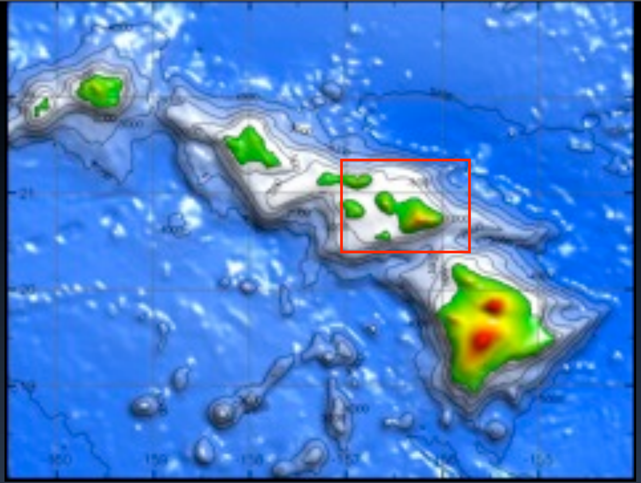




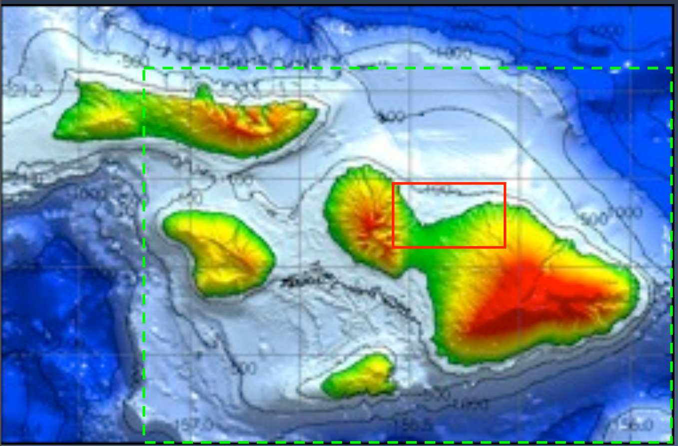


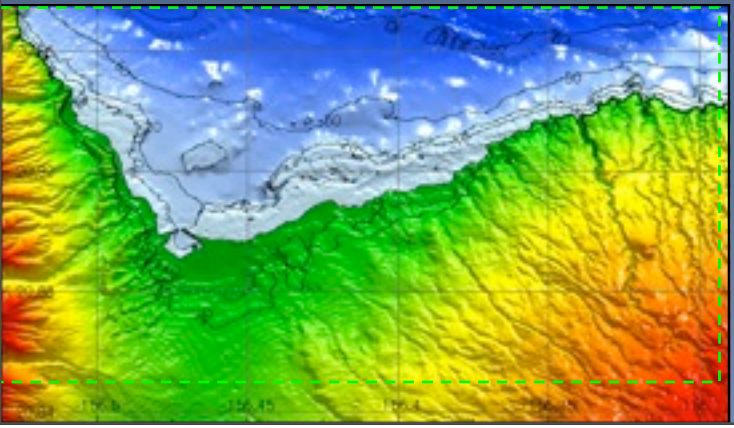


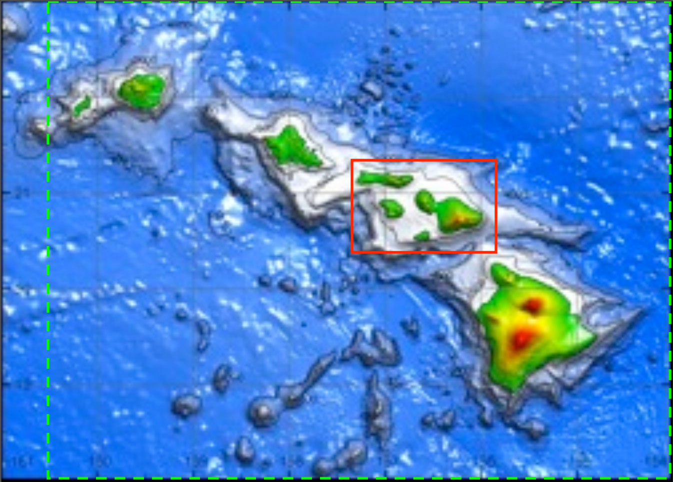




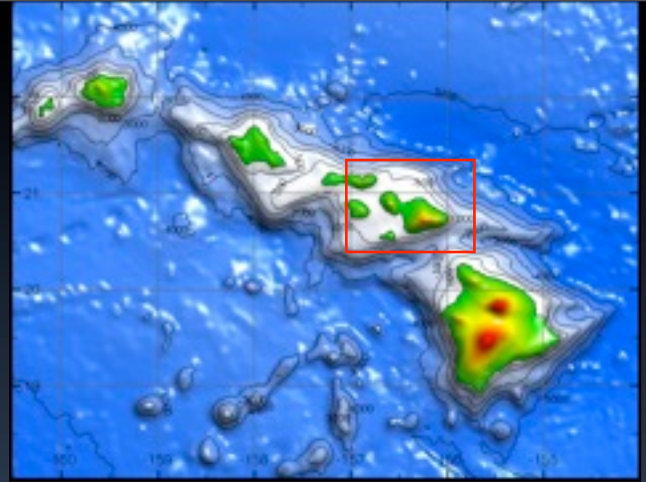
Resolution: 36” to 120”
Grid Size: 700x500 to 196x150
Time Step: 2 to 12 sec

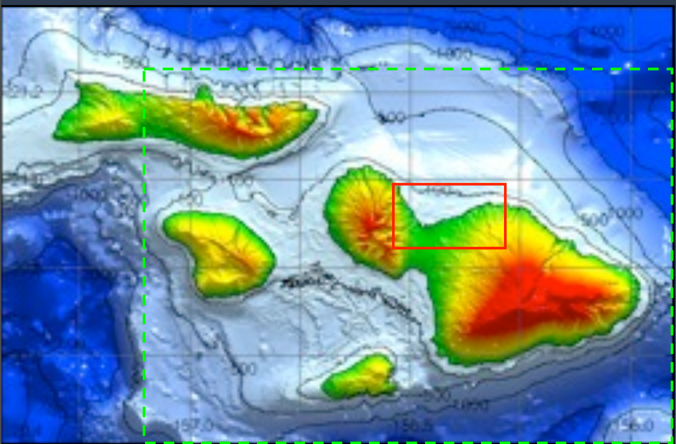




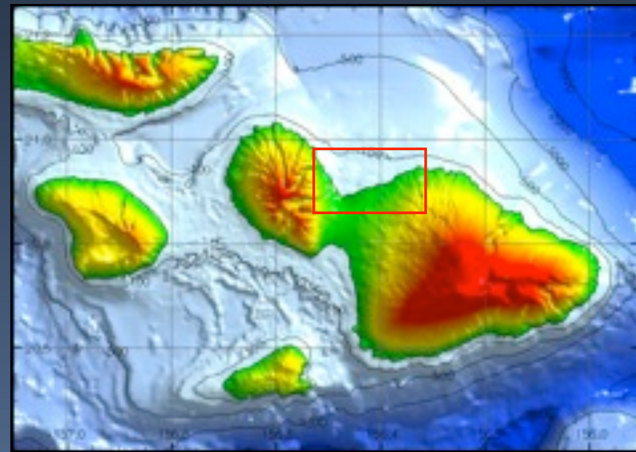


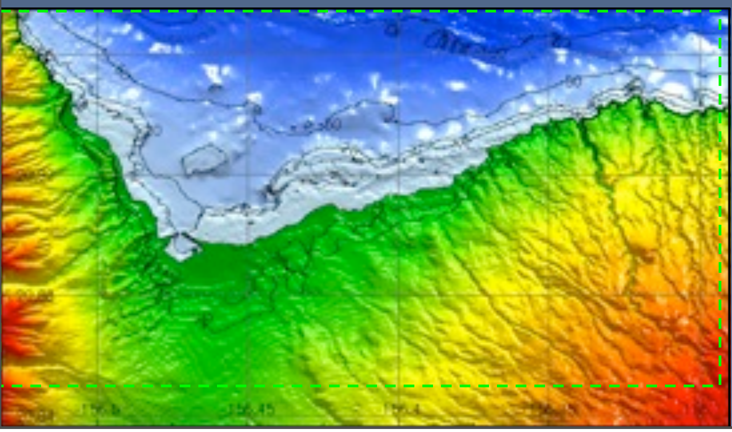
Resolution: 36” to 120”
Grid Size: 700x500 to 196x150
Time Step: 2 to 12 sec

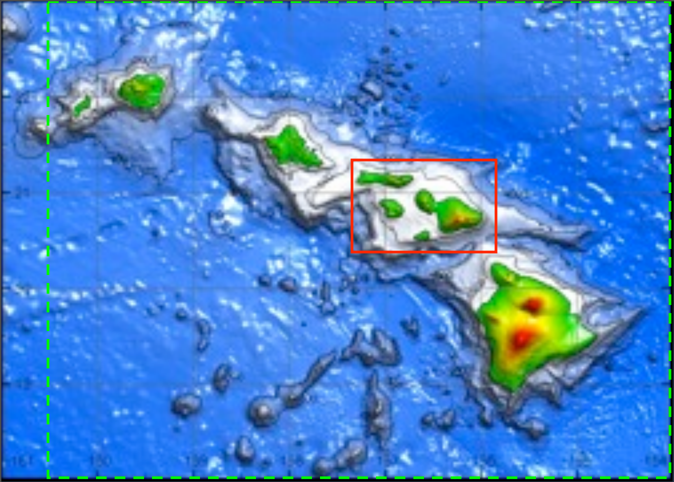


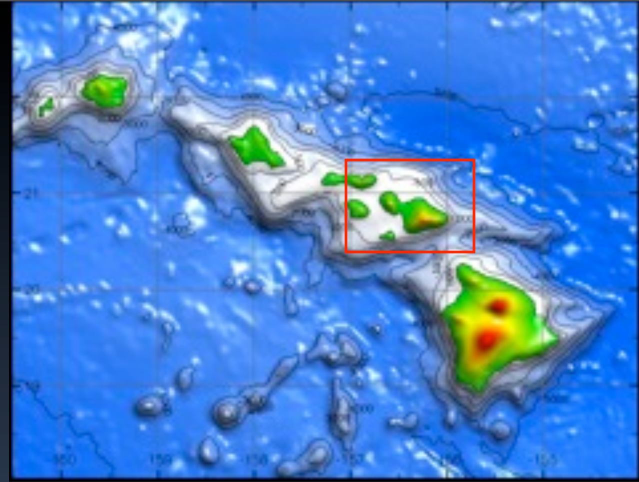


Resolution: 6” to 12”
Grid Size: 917x597 to 361x257
Time Step: 0.4 to 1.5 sec

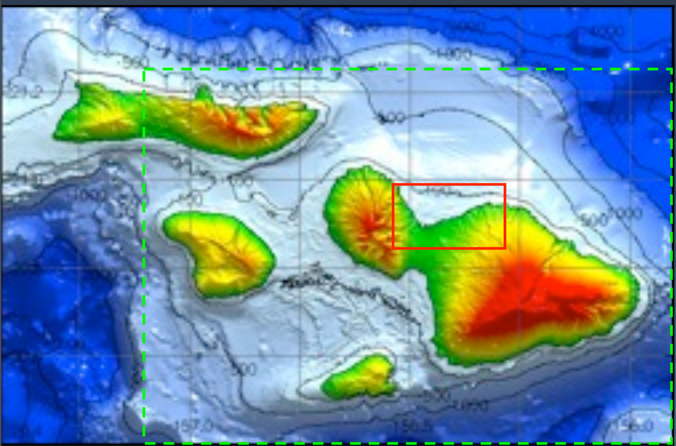


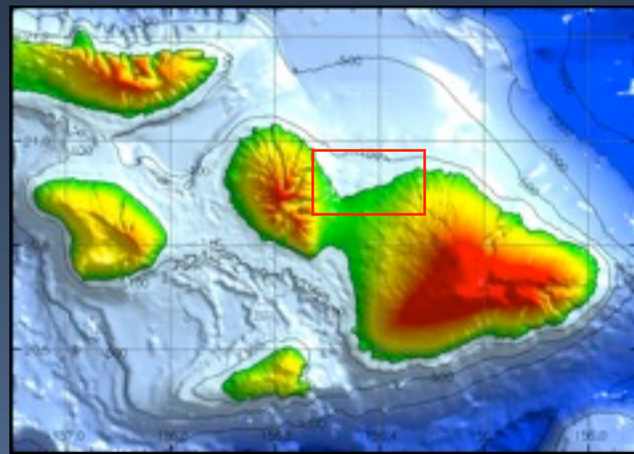






Resolution: 36” to 120”
Grid Size: 700x500 to 196x150
Time Step: 2 to 12 sec





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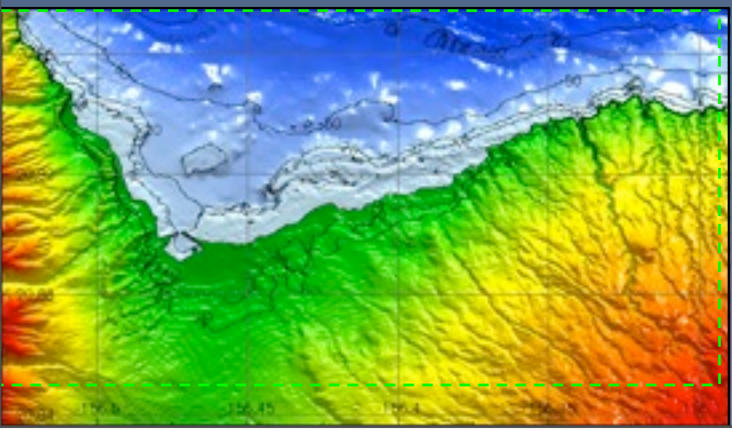
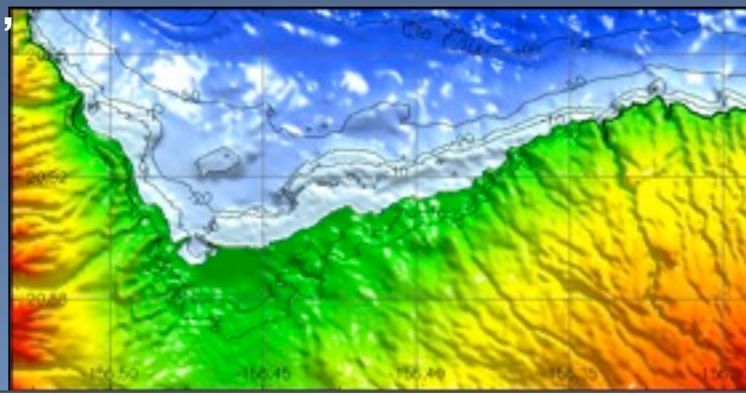
Time Step: 0.4 to 1.5 sec

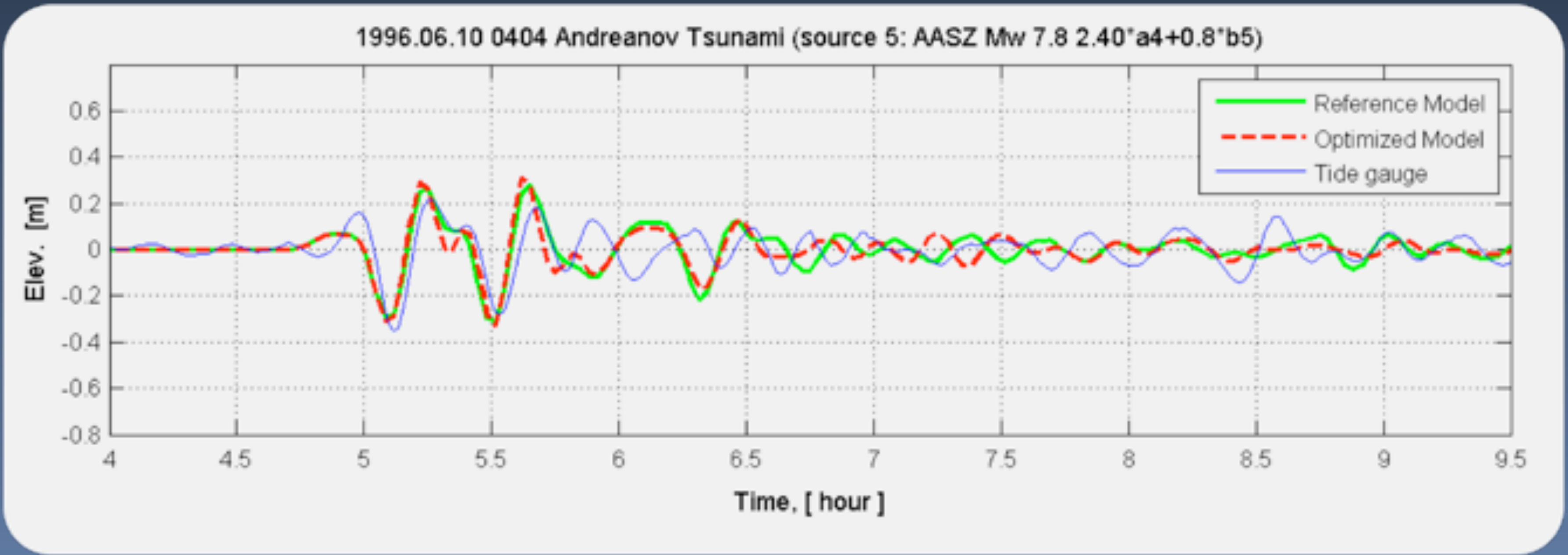




Resolution: 1” to 13”
Grid Size: 872x500 to 291x150
Time Step: 0.2 to 1.5 sec
Run Time: 8+ hours to 10– min

Creation of the SIM Set of Grids

Monitor time series degradation at Warning Point and/or Tide Gage by comparison with Reference Run. (No tide-gage data available for Seaside)



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